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CUSPATE SHORELINE MORPHOLOGY

by

Brandon McWilliams

June 2005

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Large beach cusps with wavelengths O(200m), sometimes termed mega-cusps, were measured along 18km of the Southern Monterey Bay coastline from October 2004 to April 2005 to investigate the cuspate shoreline response to rip current systems. Monterey Bay is a unique location for the study of rip current systems, which has with well defined rips that are present all year long, a large dune erosional rate, and incident wave energy that is primarily shore-normal with a large along-shore gradient. Contours of the coastline were extrapolated from the surveys using an all-terrain vehicle equipped with Kinematic GPS. Cusp spacing was inferred from the data using a zero up-cross technique and found to be O(230m) for low wave energy beaches and O(250m) for high wave energy beaches. Migration rates of the cusps were found to be 1-5m/day owing to the quasi-uniform erosion of the dune system. Cusps were found to be semi-permanent features with length scales dependant upon the local wave climate.

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CUSPATE SHORELINE MORPHOLOGY

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ABSTRACT

Large beach cusps with wavelengths O(200m), sometimes termed mega-cusps, were measured along 18km of the Southern Monterey Bay coastline from October 2004 to April 2005 to investigate the cuspate shoreline response to rip current systems. Monterey Bay is a unique location for the study of rip current systems, which has with well defined rips that are present all year long, a large dune erosional rate, and incident wave energy that is primarily shore-normal with a large along-shore gradient. Contours of the coastline were extrapolated from the surveys using an all-terrain vehicle equipped with Kinematic GPS. Cusp spacing was inferred from the data using a zero up-cross technique and found to be O(230m) for low wave energy beaches and O(250m) for high wave energy beaches. Migration rates of the cusps were found to be 1-5m/day owing to the quasi-uniform erosion of the dune system. Cusps were found to be semi-permanent features with length scales dependant upon the local wave climate.

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I. INTRODUCTION

A. BACKGROUND

Large cusps, sometimes called mega-cusps, having alongshore lengths of 100-1000m, are characterized by seaward protruding accretion horns and erosive embayment cusps. These cusps are differentiated from more often observed beach cusps having alongshore lengths of 10-50m. It has been hypothesized that rip currents have long been associated with the morphodynamical changes in the shoreline, with the maximum erosion occurring at the narrowest cross-section of the beach corresponding to the beach behind the cusp embayment (Bowen and Inman, 1969; Komar, 1971). Brander and Short (2000) found a scaling relationship between low and high energy rip current systems, which implies that there is a physical connection between waves, currents, and morphology.

Earlier work on beach change was based on measurements of beach morphology and assumed that waves force the beach changes with erosion and accretion cycles (Russell, 1967). Russell and McIntire (1965) identified a correlation between cusp formation (destruction) and beach accretion (erosion). Coco et. al. (2004) identified the presence of tidally modulated spatial patterns in accretion and erosion during beach cusp formation. Sunamura and Aoki (2000) have shown that the presence of large perturbations on a beach can trigger beach cusp formation.

Infragravity waves, and in particular edge waves, have been hypothesized by many authors as the forcing mechanism for much of the observed nearshore morphology inducing beach cusps, as edge wave lengths and cusps are of similar length. Masselink et. al. (1997) demonstrated that the water motion in cusp embayments is characterized by higher energy levels at the subharmonic and infragravity frequencies than at the cusp horns. Dean and Maurmeyer (1980) ascribe the generation of low frequency energy to swash interactions resulting from a horn divergent swash circulation pattern that is typically associated with beach cusp morphology. Guza and Inman (1975) suggested that the swash from incident waves is superimposed on the standing edge wave motion to produce a rhythmic longshore variation in swash height, producing an erosional

perturbation. Little evidence of edge wave forcing was found by Holland and Holman (1996) during the development of beach cusps, which was found to be clearly influenced by preexisting cuspate morphology. Masselink (1999) found that the edge wave forcing mechanism of beach cusp formation was inconsistent with the observed spatial trend of the cusp spacing, but was strongly related to horizontal swash excursion. Holman and Bowen (1982) theorized that the residual drift pattern associated with sub-harmonic edge waves could force spatial variation in the longshore direction responsible for the formation of a wide range of rhythmic morphological features. Masselink et. al. (2004) found that energetic standing, mode-zero, subharmonic edge waves were not present during the initial formation of the beach cusp morphology and therefore were not a prerequisite for the formation of rhythmic beach morphology. The problem with edge waves as a forcing mechanism is that standing, monochromatic waves are required to force morphodynamic patterns, and edge waves in nature are found to be broad banded. Therefore, the edge wave hypothesis is questionable, except under special conditions.

The initial formation and cause of rhythmic morphology has been a major topic of near-shore research for decades with little conclusive evidence proving any one concept correct. Other explanations consider rhythmic morphological features formed as a result of a self-organization concept. Werner and Fink (1993) theorized the formation of beach cusps using the self-organization concept finding that cusps were a result of a coupling of hydrodynamics and sediment transfer through both positive and negative nonlinear feedback. Reniers et. al. (2004) used a morphodynamical model to show that rhythmic alongshore features (rip channels) are the result of broad band (in direction and frequency) wave groups. The energy of the wave groups with cross-shore and alongshore scales of O (200m), force surf zone eddies of the same scale. It is found in the model that the surf zone eddies can act as the initial perturbation on a uniform alongshore beach to initiate rip currents. Once the rip channels are initiated, a positive feedback mechanism allows for the undulation to grow in time. The objectives of this study are to determine the scaling relationship of beach cusps by repeated Kinematic GPS (KGPS) surveys of shoreline to determine the correlation between embayment cusps with time, and to determine embayment cusp location and scaling to that of the dunes at the back beach.

B. STUDY SITE

Monterey Bay is a large, almost symmetric, embayment on the California coast, located approximately 100 km south of San Francisco (Figure 1). It has a gently curving shoreline approximately 48 km long, which is comprised of three littoral cells; the northern cell extends from Point Santa Cruz to the northern side of the Monterey Canyon, and the two southern cells extend from the southern side of the Monterey Canyon to Point Piños (Figure 2). The northern most of the two southern cells extends from the Salinas River north to the southern side of the Monterey Canyon, with transport to the north. The southern most cell extends from the Salinas River south to Point Piños. This study is focused on approximately 18km of sandy shoreline from Monterey Wharf #2 to the Salinas River (Figure 3). The coastline between Monterey Wharf #2 and Point Piños is composed of a rocky shoreline with small pocket beaches of granitic material where littoral transport is no longer seen and is not included.

Littoral transport in the southern cell is generally from north to south beginning at the Salinas River mouth and extending to Sand City Beach. The grain size from the river mouth south increases in size until a maximum of approximately 0.8mm at Fort Ord (wave energy is focused at Ford Ord due to refraction from the Monterey Canyon), and then decreases to a finer grain size at Del Monte Beach (Dingler and Reiss, 2002). The average significant wave heights were greater than two meters offshore with nearshore wave heights approximately one meter throughout the study (Figure 4). Wave direction varied offshore from west-northwest to southwest, however due to refraction and the headlands the nearshore waves approach from the west The significant wave heights are greater in winter (December-March) than in summer (June to September) (Xu, 1999).

C. METHODOLOGY

The nearshore morphodynamical and topographical changes were surveyed approximately bi-monthly using Kinematic GPS (KGPS) and a KVH tilt sensor mounted onto a Polaris all-terrain vehicle (ATV) (Figure 5). The KGPS has a rms accuracy of +/- 5 cm at 10 Hz. The alongshore cusp spacing is measured from Monterey Wharf #2 to the mouth of the Salinas River, a span of approximately 18 km (Figure 3). This is a convenient location, since the lab where the equipment is stored is located at the beach just north of Monterey Wharf #2. During times of spring low tides, the ATV is driven

near the water line and then back along the upper beach face (ensuring that the slope of the beach is observed) with location and tilt readings taken every second by the KGPS receiver. The north and south legs of the survey combined take approximately two hours to complete at a rate of 1 m/s. The back edge of the dune from Monterey Wharf #2 to the beach access at Reservation Road in Marina, Ca was completed on February 22, 2005 with the Polaris ATV.

1. Interpolation of the Beach Survey Data

Once the surveys are completed, the +2m contour is interpolated (extrapolated) from the beach lines measured approximately every 1m along the shoreline. The latitude, longitude, and elevation data are converted into vector form, with the positive y vector oriented in the alongshore direction pointed north and the positive x vector in the offshore direction. The curvature of the Monterey coastline is subtracted from the data to examine variations alongshore of the cuspate shoreline. An average, or generic, coastline is created by fitting splines to increments of the shoreline and matching the intercept and slope of adjoining end points of splined sections. The variations of the shoreline are the closest perpendicular point of the survey from the generic coastline. The horizontal variations in the x direction (offshore/onshore) are plotted versus the distance alongshore (positive y direction) from Monterey Wharf #2 in increments of 6 km e.g. Figure 6.

a. Cusp Length Scale Determination

The cusp spacings alongshore were measured using the zero up-cross method. A cusp is defined as the distance between adjacent zero up-crosses. The average length scale of the cusps is determined by dividing the distance of shoreline by the number of zero upcrosses. The zero up-cross method is sensitive to high frequency noise of the shorter length beach cusps and low frequency variations. Therefore, it is necessary to band pass filter the signal before analysis.

The low frequency variation are the curvature of the shoreline and some long (>500 m) shoreline variations. The filtering was accomplished by using a Fast Fourier Transform (FFT) filter. The alongshore variations for each survey that were passed through the FFT, and the complex coefficients outside the band of interest were zeroed. Each time series, and segments within those time series, were filtered to a different degree (high and low cutoff points) to obtain a signal that represented the

smaller scale cusps migrating atop the larger scale features (Table 1). An inverse FFT was performed to obtain the filtered signal (this is discussed in section III B.).

b. Correlation of Survey Data

Each subsequent data set was cross-correlated with the first data set from 10/28/04 to estimate the degree to which the spatial series de-correlated. Segments of the coastline, 0km–6km, 6km–11km, 11km–16km, and 16km–18km, were used for cross-correlations because the spatial scales of the data varied alongshore i.e., were inhomogeneous. The point at which the data becomes decorrelated is determined by the e-folding scale (1/e is used here). The data sets quickly became decorrelated, so the correlation sequence was restarted with the 12/11/04 survey and each subsequent data set were cross-correlated to it.

c. Cusp Migration Times

The cusp migration is determined by the displacement of the peak cross-correlation with the time between surveys. Positive displacement represents northward migrating cusps and negative represents southward migrating cusps. Migration times can be meaningfully tracked until the data is no longer correlated. Cusp migration rates were also calculated by tracking strong (obvious) cusp signals from the sequential surveys and dividing by the time between surveys.

2. Interpolation of the Dune Toe Data

a. Dune Toe Analysis

Since the dune erosion occurs episodically, the dune toe was measured only once on February 22, 2005 by driving the ATV along the base of the dune. The dune toe was surveyed as late in the winter as possible not to exceed March 1, 2005, to measure the effects of the past winter on the dune toe. After March 1st, the western snowy plover (*Charadrius alexandrinus nivosus*) mating season begins and all ATV traffic on the dunes is prohibited. The dune toe survey data were treated in the same manner as the +2m contour data by subtracting the general coastline to obtain horizontal variation. The dune toe variations are plotted against the distance from Wharf #2 (positive y vector). The dune toe variations are cross-correlated with the +2m beach contour to determine the extent that the embayment cusps and accretion horns are correlated with the location of the dune toe.

3. Stillwell Hall Survey Analysis

Stillwell Hall was built about 100m from the dune edge in the 1940's as the Fort Ord soldier's club in Marina, California. Owing to a historic erosion rate is 2-3 m/yr a rock revetment was built to protect Stillwell Hall (Figure 7). The wall was approximately 200 m in length and was built in 1976 and added onto in 1983 (Thornton, 2005). The rock revetment created a classic example of passive erosion where the adjacent shorelines continue to erode on each side of the shoreline fixed by the revetment. Over time the revetment projects into the ocean (Figure 7). Stillwell Hall was demolished in 2002, and the rock revetment was removed by March 2004 (Figure 8). After the revetment was removed, a pile of sand projected seaward of the normal beach line and rapidly eroded with time. The dune toe at Stillwell hall (from approximately 9300m to 9700m north of Monterey Wharf #2) was included in each survey to monitor the erosion. This will be addressed separately in the analysis.

II. ANALYSIS

A. DATA FROM SURVEYS (+2M CONTOURS)

The +2m contour surveys along the southern Monterey shoreline all show variability about the mean shoreline (Figure 9). From Monterey Wharf #2 north to Sand City (approximately 5km) there are large scale cuspate features on the order of 600m, with beach cusps overlying the larger features with scales on the order of 200m. The large scale cuspate features were found not to exist north of Sand City and the cusp lengths decreased to 200m north of Sand City (Table 2). Cusp width (embayment to horn) varied alongshore. The variations were greater, O(25m), for low wave energy (<1m), and the cusp width became less varied with higher energy wave conditions (>2m). This is evident in the southern most 5km, where wave energy was consistently low with the cusp width variations O(20m) throughout the study, compared with Fort Ord where the wave conditions were generally high and the variations O(5m) for most of the surveys. The width variations decrease to O(5m) along the coast north of Sand City to the northern end of the Fort Ord beaches. Variations then increase to O(10m) north of Fort Ord to the Salinas River as the mean wave energy decreases.

1. Cross-Correlation +2m Data Sets

The shoreline surveys are cross-correlated using the first survey as a reference. Sections of the shoreline are used since the scale of the cusps is inhomogeneous alongshore. The data from 0km-6km are highly correlated, where the maximum cross-correlation after the seven month period has only decreased to 0.87 (Figure 10). Maximum spatial lag is -61 m (negative lag is southerly) and occurs with the 11/24/04 survey data (Figure 10). The data from 6km–11km section becomes de-correlated by the 03/08/05 survey, and the maximum cross-correlation with the sequential dates never lags more than 90m before de-correlation, with the lags drifting back and forth about the zero lag position (Figure 11).

The data from 11km–16km range becomes completely de-correlated by 02/08/05 (Figure 12). The initial autocorrelation of 10/28/04 has a much wider peak than the previous range of 6km–11km (Figure 12) indicating longer length cusps. The data series from 16km-18km stays correlated throughout the time period and, like the first two data

sets, the lag varies about zero with the maximum lag of -343m on 03/21/05 (Figure 13). The peak cross-correlations and lag distances are plotted against time in Figure 14 to determine decorrelation times. Maximum correlations decrease over time at approximately an exponential rate, which is at a maximum in the 11-16km range (Figure 14).

2. Wave Data

The Monterey Buoy (Station 46042) is located approximately 27 NM west of Monterey Bay, California (36°45'11" N 122° 25'21"W) and is owned and maintained by the National Data Buoy Center. The ADCP instrument is located at Sand City (36º 37’12”N 121º 51’43”W) at an approximate depth of 13m. Wave heights obtained from the offshore Monterey buoy visually corresponds to the nearshore ADCP wave heights (Figure 15). The hourly wave heights from the two sources are compared by linear regression (Figure 16) and found to be significantly correlated (Figure 17). A best fit linear line (with a slope of 0.42 and an r^2 value of 0.56) was calculated from the data points showing that the ADCP wave heights have a positive correlation with the wave heights of the offshore buoy. The r^2 value was determined by squaring the covariance of x and y (values of the wave height data in relation to the linear regression line) divided by the standard deviation of x and y. The ADCP in Sand City does not receive the waves from southerly directions due to the protective headland of Point Piños. Therefore, the r^2 value of 0.56 was obtained after deleting all wave height data that was greater than 50° south of shore-normal (313°) at the offshore buoy data. An r^2 value of 0.47 was obtained when using all data. The ADCP wave height data were cross-correlated with the Monterey offshore buoy, with a maximum correlation of 0.76 (Figure 17).

B. RIP SPACING

1. Length Scales of Embayment Cusps

The average lengths of cusps were analyzed every 1000 m and were found to vary both alongshore and between survey dates. The mean cusp length from all 18 km was 222 m with a standard deviation of 46 m (Table 2). Over the 18 km of shoreline there was no real trend of cusp spacing, with the exception of smaller cusp spacing between 5-7 km and larger cusp spacing for 13-14 km.

The variation of the cusp lengths about the mean is given by the coefficient of variance. The Coefficient of Variance (CV), defined as the standard deviation divided by the mean, was calculated every 1000 m and was found to have an average value of 0.20 (Table 2). This states that the cusp lengths varied only approximately 20% of the mean cusp lengths.

2. Migration Time Scales

Mean migrations of cusps are quantitatively observed by comparing surveys. Quantitative measurements of migration rates are obtained from the spatial lag of the maximum correlation as a function of time. Cusp migration was particularly evident between the 03/08/05 and the 03/21/05 surveys. Several examples of clear cusp migration were chosen along the coastline to measure the cusp movement, and were found to be of O (7m/day) or 100m per survey interval of 14 days. The areas chosen were at approximately 3500m, 6300m, 11.4km, 13.7km, and 17km north of Monterey Wharf #2 corresponding to different wave conditions along the shoreline (Table 4).

Migration direction is determined by wave direction, with migration directions being both north and south corresponding to the waves during and before the survey dates. The embayment cusp migration rates are given in Table 4. Average migration rates of 0.5m/day, 0.9m/day, 2.4m/day, and 5.2m/day, corresponding to 0-6km, 6-11km, 11-16km, and 16-18km, generally increase with increasing distance from Monterey Wharf #2 with the exception of the 11-16km data which quickly decorrelates.

C. DUNE TOE CONTOUR CORRELATION

1. Back Beach Correlation with +2m Contour

The toe of the back beach was surveyed on 02/22/05 up to Reservation Road in Marina, CA; approximately 14km north of Monterey Wharf #2. However, the dune toe data was unable to be correlated with the 02/22/05 +2m beach contour data due to a mechanical problem with the ATV, which made it impossible to obtain the survey. The 0-6 km dune toe data is cross-correlated with the previous +2m beach contour survey data with a maximum correlation of 0.39 and a -92m lag (Figure 18). The 0-6 km dune toe data was also correlated with the next +2m beach contour survey and there was a maximum correlation of 0.38 with -111m lag (Figure 19), which are both significantly correlated at the 95% confidence interval.

The cross-correlation with the +2m beach contour data for 6km-11km had a maximum correlation of 0.06 with 18m lag and 0.08 with 266m lag for 02/08/05 and 03/08/05 respectively (Figures 20-21), which are not significantly correlated. The cross-correlation with the +2m beach contour data for 11km-14km had a maximum correlation of 0.35 with 342m lag and 0.20 with 41m lag for 02/08/05 and 03/08/05 respectively (Figures 22-23). The region of the data between 6km and 14km shows no correlation between the cusps in the beach contours and the dunes that back the beach.

D. STILLWELL HALL PROMATORY EROSION

1. Stillwell Hall Dune Survey

A noticeable promontory of sand was left after the removal of the coastal armoring in March 2004 at the base of the dune. The survey plots are time-stacked atop one another in order to determine the erosional areas of the dune over time. A comparison of the dune toe surveys along with +2m contour surveys at the same time shows a definitive trend of erosion at the northern end of the dune (Figure 24). There is marked beach erosion and scarping of the dune toe at the southern end of the dune due to the location of an erosive embayment cusp (Figure 25). The northern end of the dune is initially protected by an accretive horn and the scarping of the upper beach and erosion of the dune is not as prominent.

III. DISCUSSION

A. +2M BEACH CONTOUR SURVEY

The greatest degree of beach mobility has been found to be associated with intermediate and highly changeable wave conditions, medium grain sediments, and a modest to meager sediment supply (Wright and Short, 1984). On the low tide terrace beach state, such as found in Southern Monterey Bay, the bar is in close proximity to the beach face, thus allowing rapid exchange of sediment and leading to higher temporal variability. With this reasoning, the shoreline response to low energy events should be less than the response to high energy events. This can be seen by quantitatively comparing the +2m beach contours with the wave energy for the same time period. The region of 11-16km associated with focusing of higher wave energy due to refraction is observed to decorrelate faster than the other regions with lower wave energy.

Masselink et. al. (2004) determined that cusp evolution was strongly linked to the offshore wave and tide conditions, with the formation of new cusps occurring during periods of accretive low wave energy ($H<1m$) and cusp destruction occurring during periods of erosive high wave energy ($H>2m$). The decorrelation of the data in the 11-16km segment during periods of erosive wave conditions indicates a coupling between the local wave condition and the shoreline response. The destruction of the cusps in the shoreline during erosive wave conditions results in decorrelation of the data, and as accretive wave conditions reform the cusps, the data becomes correlated again, as seen in the data from the 11-16km segment (Figure 12).

B. RIP SPACING

The evolution of rip current spacing and the mechanisms behind their development are, so far, not well understood. Rip current spacing has been theoretically scaled to surf zone width by Huntley and Short (1992), Hino (1974), Falques et. al. (1999), and Deigaard (1999) amongst others. Brander and Short (2000) attempted to relate the spatial scales of rip currents to the local wave climate, morphology, sediment size, and the tidal conditions with little observed or analytical correlation with actual conditions.

A zero up-cross technique is used to define cusps in the data record. There were inherent problems with the automation of data analysis to measure cusps. The unfiltered plots of the horizontal position versus length were too noisy to accurately count the cusps. A Fourier filter was used to filter the data. High and low wavenumber cutoffs were chosen by a trail and error process. The high wavenumber cutoff corresponding to a wave length of 50m was chosen to eliminate beach cusps, which occur frequently with a range between 20-50m (compare Figure 24 with 25). The low wavenumber cutoff proved more difficult. Ranges of wavelength 200-2000m cutoff were calculated, with a final decision of 250m chosen for the low wavenumber cutoff (Table 4). Wavenumber cutoff corresponding to lengths on the order of 1000m did not account for the cusps of the O(200m) that were superposed on the longer spatial variations (Figure 26). The cutoff length was lowered until 250m was reached and the large scale features were removed and the cusps were able to be accurately counted (Figure 27). The wavenumber corresponding to 200m displaced too many cusps that were not being counted automatically.

An alternative approach would be to use a wavelet analysis. It is recommended that this approach to be applied to future analysis.

Rip spacing was on the order of 230m for the first 2km (corresponding to Del Monte beach to the Del Monte Hotel) where wave energy is low. Rip spacing decreases to the order of 180m by approximately 6km north of Monterey Wharf #2 (corresponding to Sand City north to Fort Ord) and after 12km (corresponding to north of Marina to the Salinas River) the spacing begins to increase to the order of 250m. The increased rip spacing appears inversely proportioned to wave energy.

1. Migration Times/Rates

The observed migration rates of 1-5m/day that were of the same order found by Brander and Short (2000) in bar migration (2-6m/day) on a similar beach at Muriwai Beach in New Zealand. The migration rates from the lag measurements of 2-6m/day were slightly lower than the measurements from the raw data, but were similar. The migration rates from the raw data do not represent as accurately the mean length scale because they are tracking specific cusp movements.

C. DUNE TOE CONTOUR CORRELATION

Foredunes can be characterized by lateral morphodynamical variation, often displaying a cusped form alongshore. However, the dune toe data, with the exception of the 0-6km range, does not correlate with the +2m beach contour data.

D. STILLWELL HALL PROMONTORY EROSION

Marked erosion of the dune at Stillwell Hall dune has occurred since the removal of the coastal armor. This in turn has increased the sand supply budget for the down-draft beaches of the littoral cell, which would be expected to widen the beaches and prevent the wave energy from eroding the dunes and cliffs.

Erosion did not occur uniformly across the protruded dune. The toe was surveyed shortly after the removal of the rip rap on 9 April 2004. The toe eroded only slightly over the spring and summer until the next survey on 28 October 2004. With the onset of winter waves, the pile of sand eroded rapidly (Figure 28). The progression of dune erosion clearly shows that the erosion is greatest in the lee of the cusp embayments. Highest erosion initially occurs in the lee of the rip embayment at the southern end of the dune toe between the October survey and the next survey in December. However, the rip embayment is not stationary and can be seen to progress northward (Figures 29-30). This in turn erodes the dune in a more northerly position in each progressive survey. When time stacked, the Stillwell Hall dune surveys possess a northward trend in the erosion of the dune (Figure 28). The rip embayment can be seen at the northern end of the dune from a visual image taken from a plane flying at a constant level of 1000ft on February 5, 2005 which is consistent with the data from the surveys between 01/07/05 and 02/08/05, which illustrates the northern progression of the erosion (Figure 31). Erosion of Stillwell Hall on 02/08/05 is more northerly, corresponding to the accretive horn, when compared to the erosion on the 01/07/05 survey (Figures 29-30).

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IV. CONCLUSIONS

A. CONCLUSIONS AND SUMMARY

The nearshore and morphodynamical changes of approximately 18km of Southern Monterey Bay were surveyed bimonthly using and ATV with kinematic GPS. The predominant morphology of the shoreline are large scale cusps, O(200m), or mega cusps. A +2m beach contour was extrapolated from the data which exhibits a variable degree of variation about a mean coastline. Sequential 6km sections of coastline of the +2m contour were found to be positively correlated over the approximately six month period of the study, with the exception of the area of coastline from 11-16km. The correlation was inversely dependant on local wave energy. The fastest decorrelation time was 57 days, indicating that the bimonthly survey frequency was appropriate. A predominant westerly offshore wave direction provided a shore normal wave climate nearshore, with offshore and nearshore waves highly correlated.

Mega-cusps in the Southern Monterey Bay possess a distinctive length scale that is related to the wave characteristics along the coastline. The cusp length scales were analyzed from a zero up-cross technique of filtered +2m contour data. The cusp lengths averaged O(220m) with a standard deviation of 46m. Length scales of the cusps were found to be larger for higher wave heights located at the Fort Ord area. Cusps were found to be migratory and dependant on wave direction. Migration rates of 1-5m/day and appeared to be a function of wave energy, with rates increasing as wave energy increased. Migration rates generally increase with increasing distance from Monterey Wharf #2.

The dune toe was surveyed on February 22, 2005, and with the exception of the coastline from 0-6km, the dune toe was found to be uncorrelated with the +2m beach contour.

A 200m rip-rap revetment was removed at the former Stillwell Hall location in March, 2004, which resulted in a mound of sand protruding onto the beach. The erosion of this large pile of sand was monitored by surveying the dune toe. The dune toe surveys taken at the Stillwell Hall site possessed a northward trend of erosion, which visually correlated to the location of the rip embayment. Erosion was greatest at the rip

embayment where the beach was the narrowest and the dune most vulnerable to waves, eating away at the dune. As the cusp, and therefore rip, migrated north, the maximum erosion shifted north on each successive survey.

APPENDIX. FIGURES AND TABLES

A. FIGURES

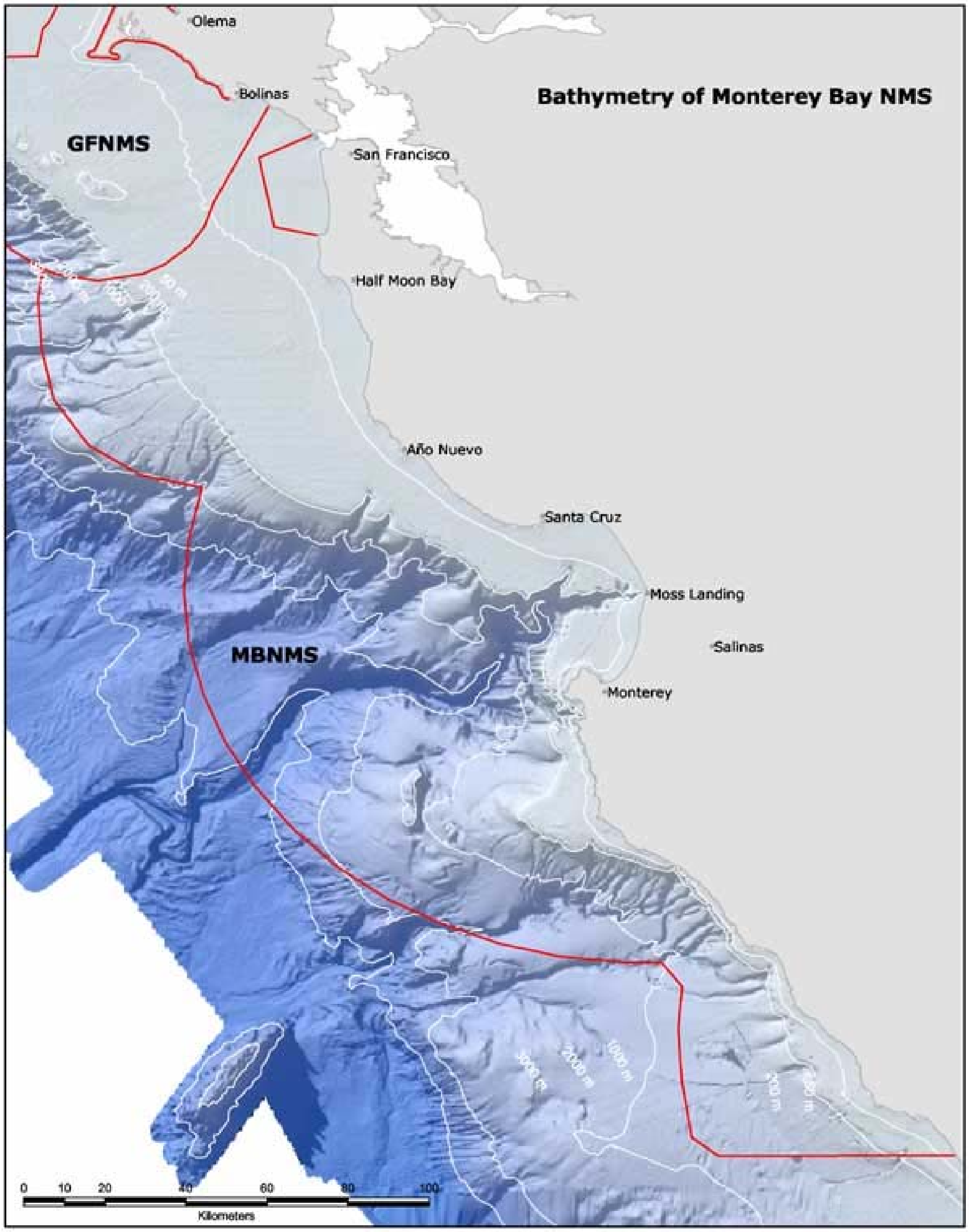

Figure 1. Location of Monterey Bay, approximately 100 km south of San Francisco (from Sanctuary Integrated Monitoring Network (SIMoN) web site http://www.mbnms-simon.org/sections/estuaries/project_info.php?pid=100116&sec=e). Site was last accessed June 2005.

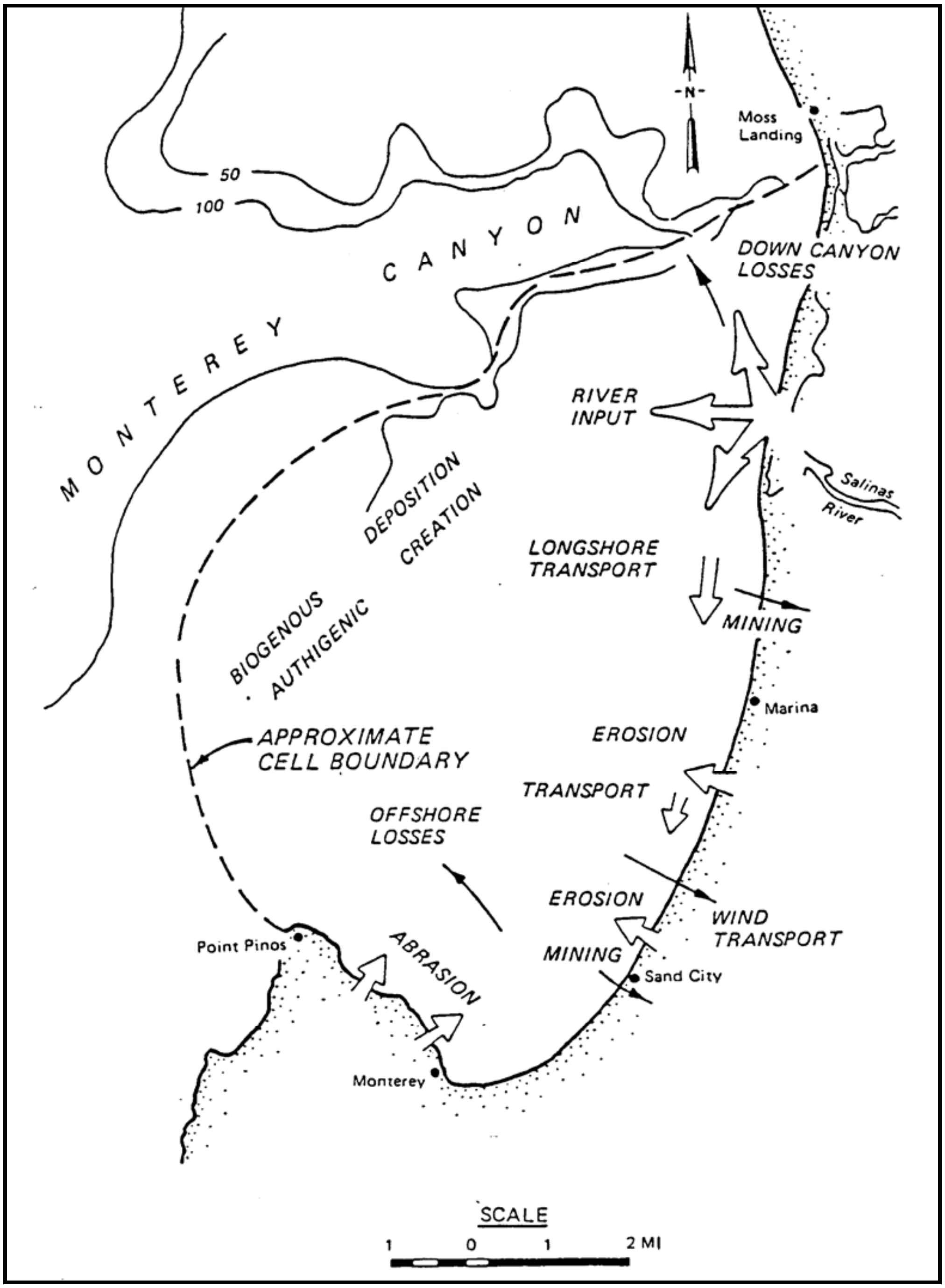

Figure 2. Southern Monterey Bay is divided into two littoral cells. The northern most of the two southern cells extends from the Salinas River north to the southern side of the Monterey Canyon, with transport to the north. The southern most cell extends from the Salinas River south to Point Piños, with transport to the south.

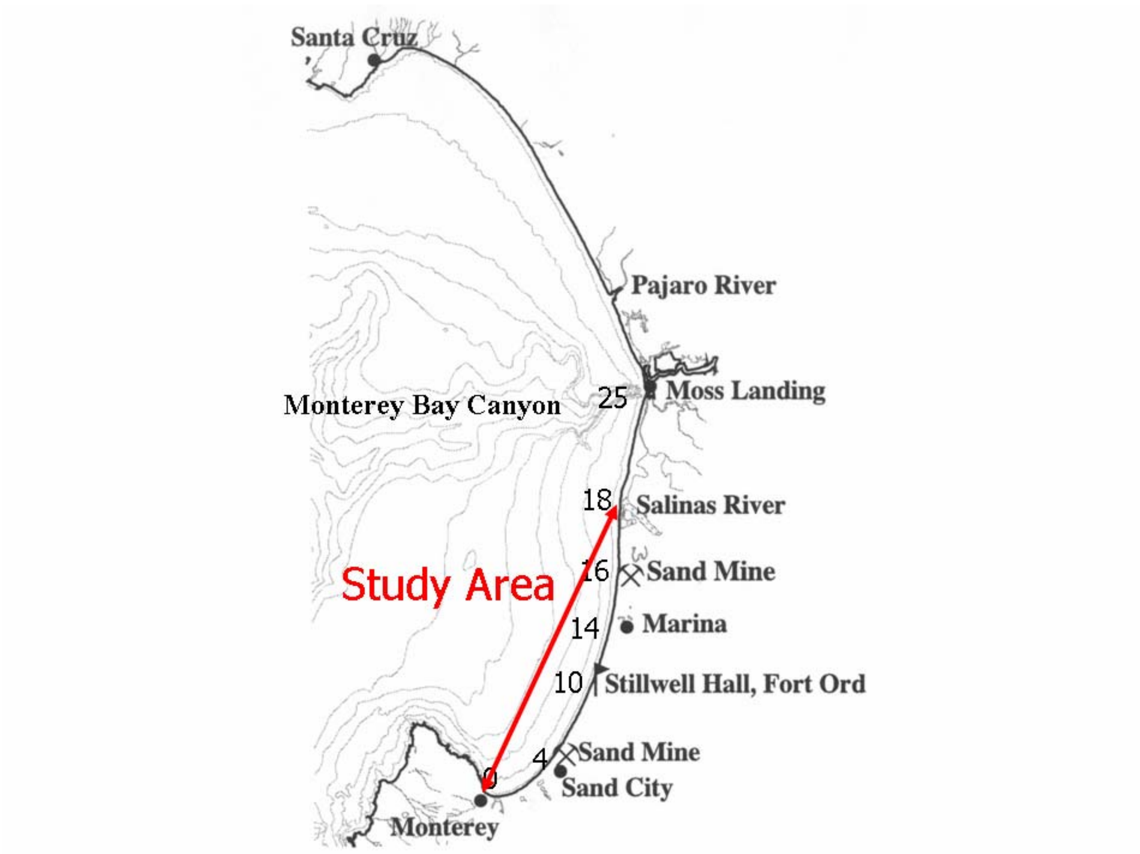

Figure 3. Southern Monterey Bay study site is approximately 18 km of coastline from Monterey Wharf #2 north to the mouth of the Salinas River.

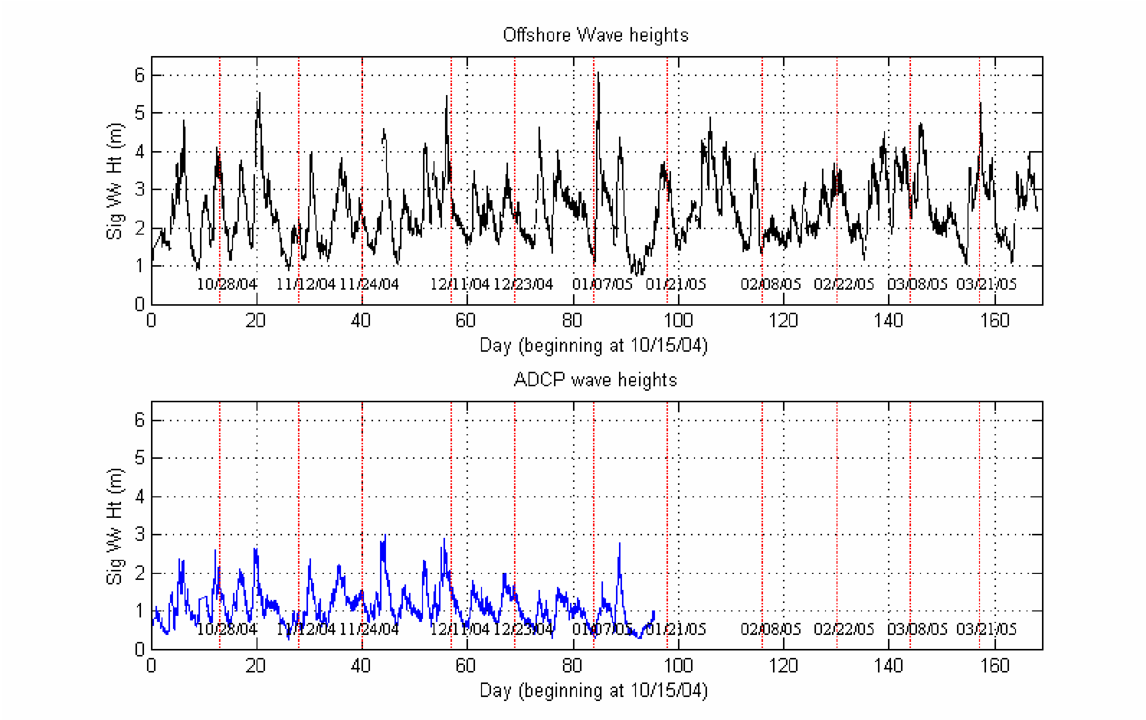

Figure 4. Significant wave heights in Monterey Bay during the 2004-2005 winter. Offshore wave heights (top) from the offshore Monterey Bay buoy (station 46042) and ADCP wave heights (bottom) at Sand City in 12.8m water depth.

Figure 5. Polaris all-terrain vehicle (ATV) with kinematic GPS (KGPS) and KVH tilt sensor hard mounted.

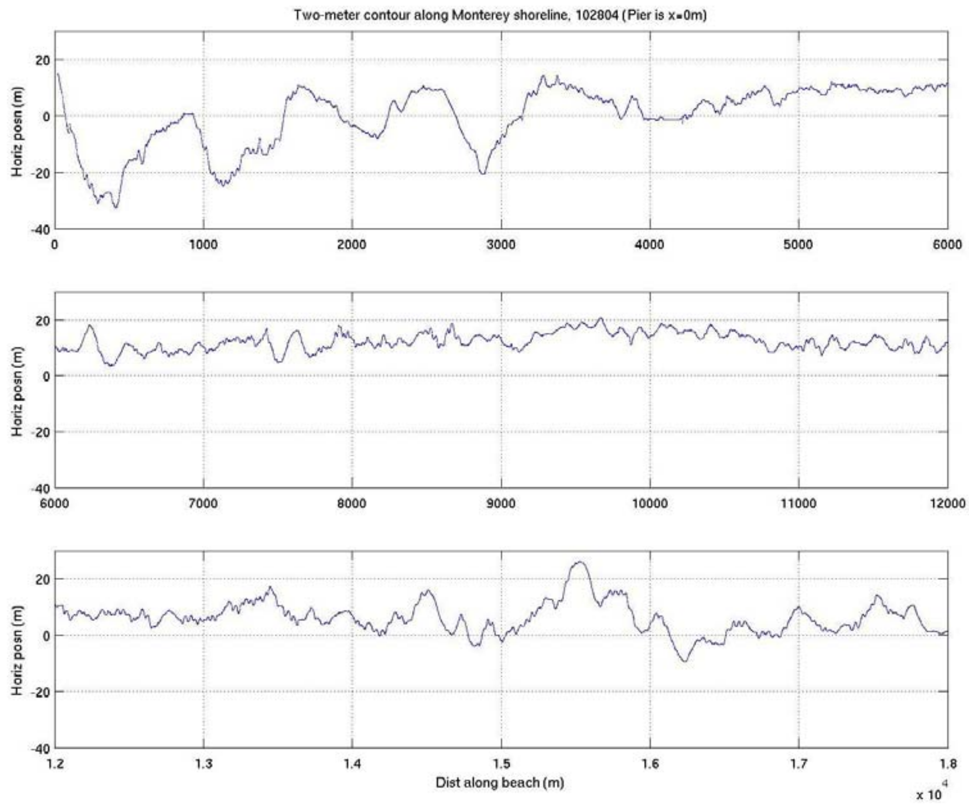

Figure 6. An example of the +2m beach contour data plotted versus distance north of Monterey Wharf #2. The data is from the 10/28/04 survey, which was the starting date for this study.

Figure 7. Oblique aerial photograph of Stillwell hall in 2002 in Marina, CA. The rock revetment can be seen at the base of the dune and marked erosion can be seen on either side of the revetment. Photograph copyright © 2002 Kenneth & Gabrielle Adelman (http://www.californiacoastline.org/).

Figure 8. Oblique aerial photograph of the former Stillwell Hall location after the building and associated coastal protection structures were removed in March 2004. Erosion has encompassed the portion of the dune that the building was atop and the vegetation in no longer present on the face of the dune as the dune is transformed back into the natural dune line. Photograph copyright © 2002 Kenneth & Gabrielle Adelman (http://www.californiacoastline.org/).

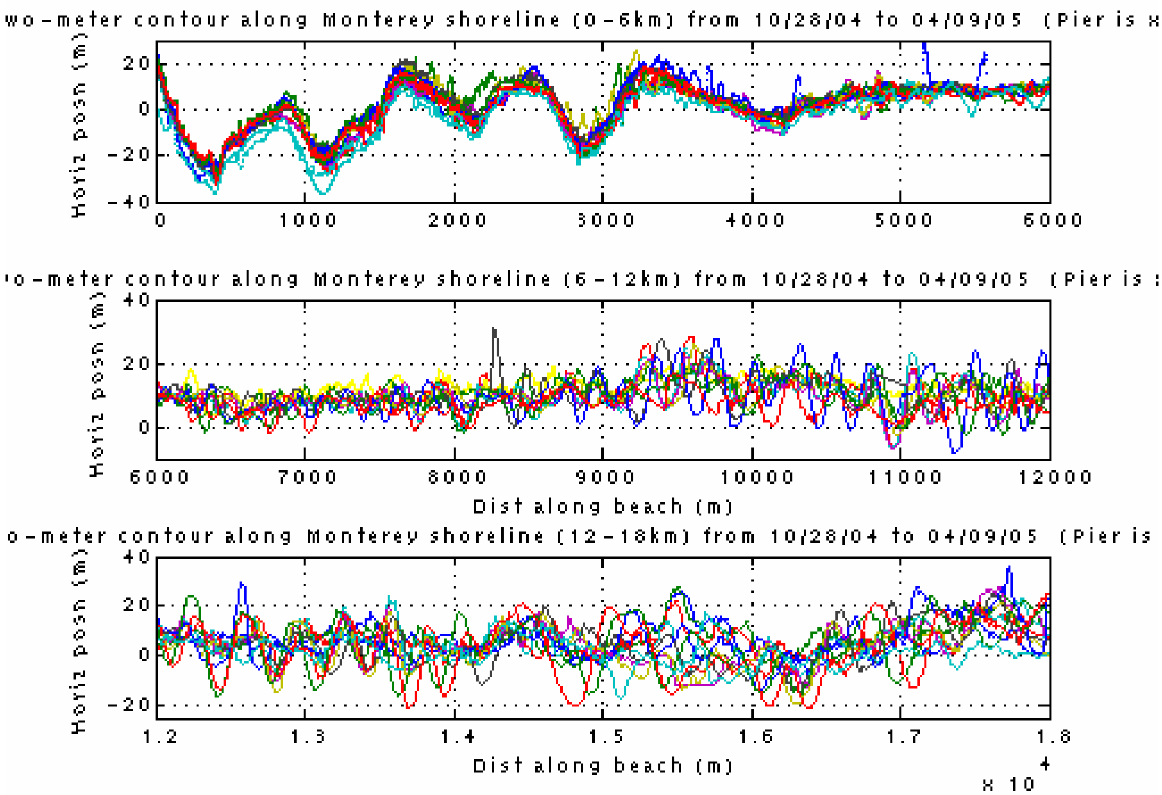

Figure 9. Overlay of all surveys showing the large cusps (O (800m)) from 0-5000m. Cusp size and spacing both decreases in the northward direction until approximately 9000m. North of 9000m, the spacing is O (250m). After approximately 5000m north of Monterey Wharf #2 the cusps become extremely varied.

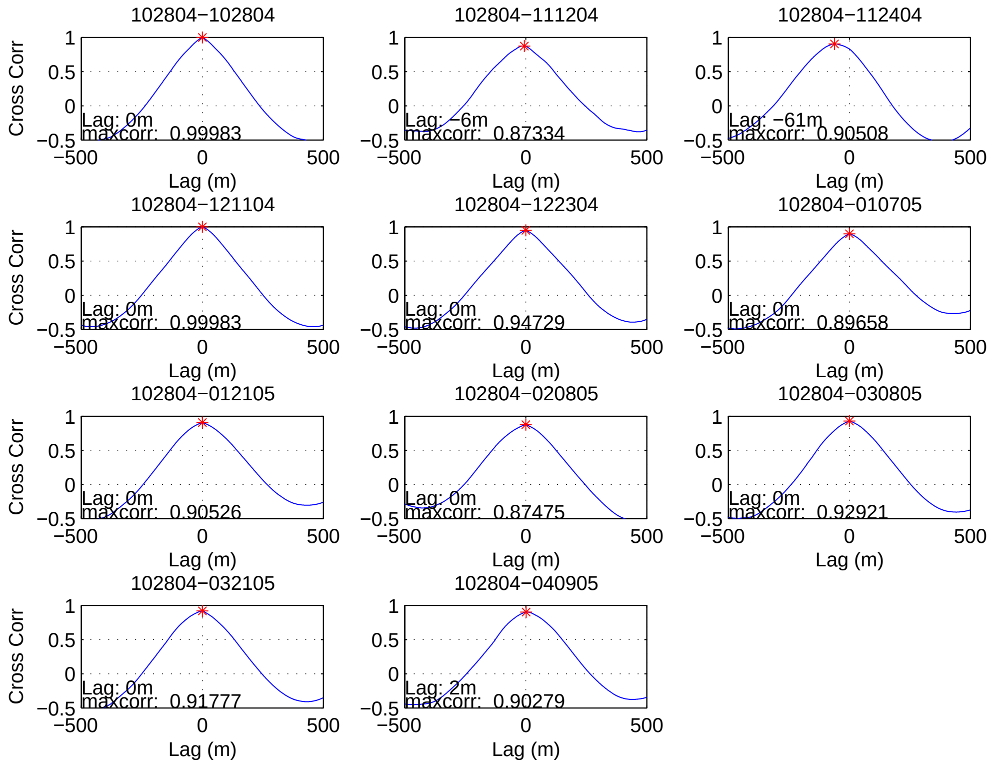

Figure 10. Normalized cross-correlations of +2m beach contour surveys for 0-6km distance south to north starting at Monterey Wharf #2 from 10/28/04-04/09/05. Cross-correlations sequence was restarted at the December 11, 2004 survey due to a large storm that affected the beach prior to the survey.

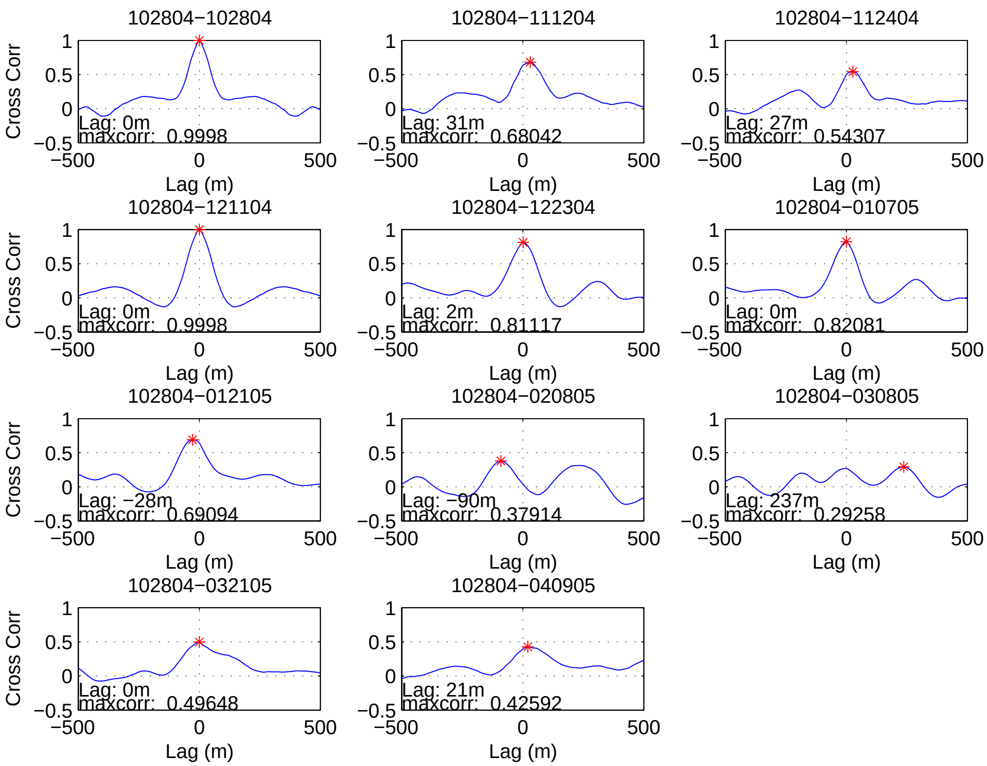

Figure 11. Normalized cross-correlations of +2m beach contour surveys for 6-11km distance south to north starting at Monterey Wharf #2 from 10/28/04-04/09/05. Cross-correlations sequence was restarted at the December 11, 2004 survey due to a large storm that affected the beach prior to the survey.

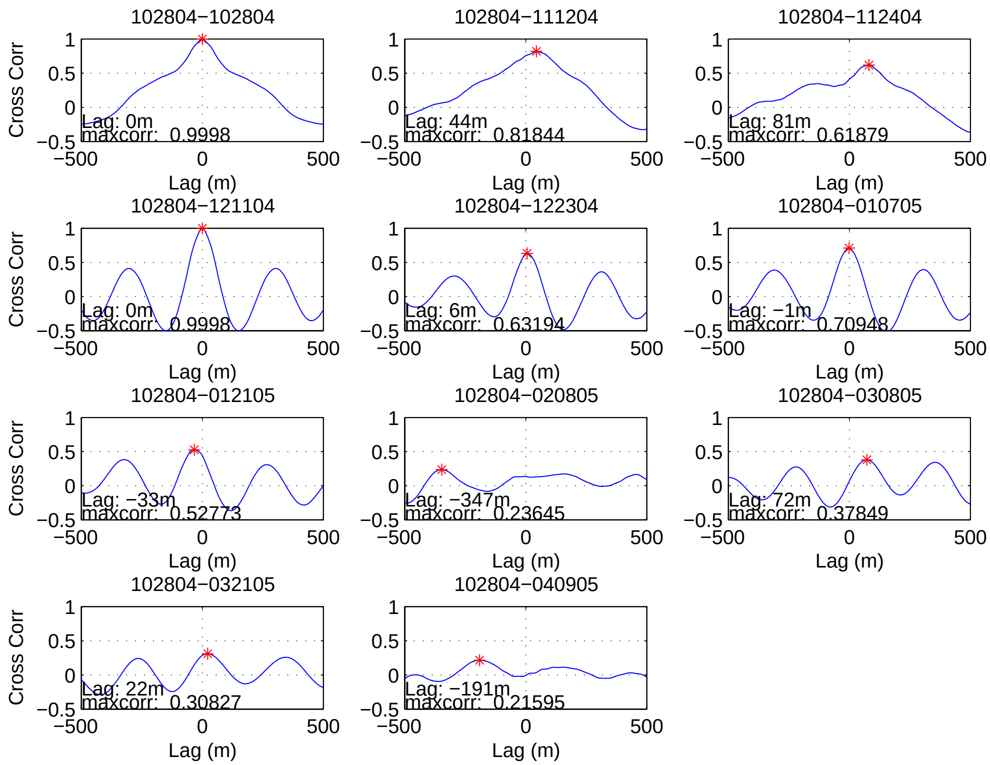

Figure 12. Normalized cross-correlations of +2m beach contour surveys for 11-16km distance south to north starting at Monterey Wharf #2 from 10/28/04-04/09/05. Cross-correlations sequence was restarted at the December 11, 2004 survey due to a large storm that affected the beach prior to the survey.

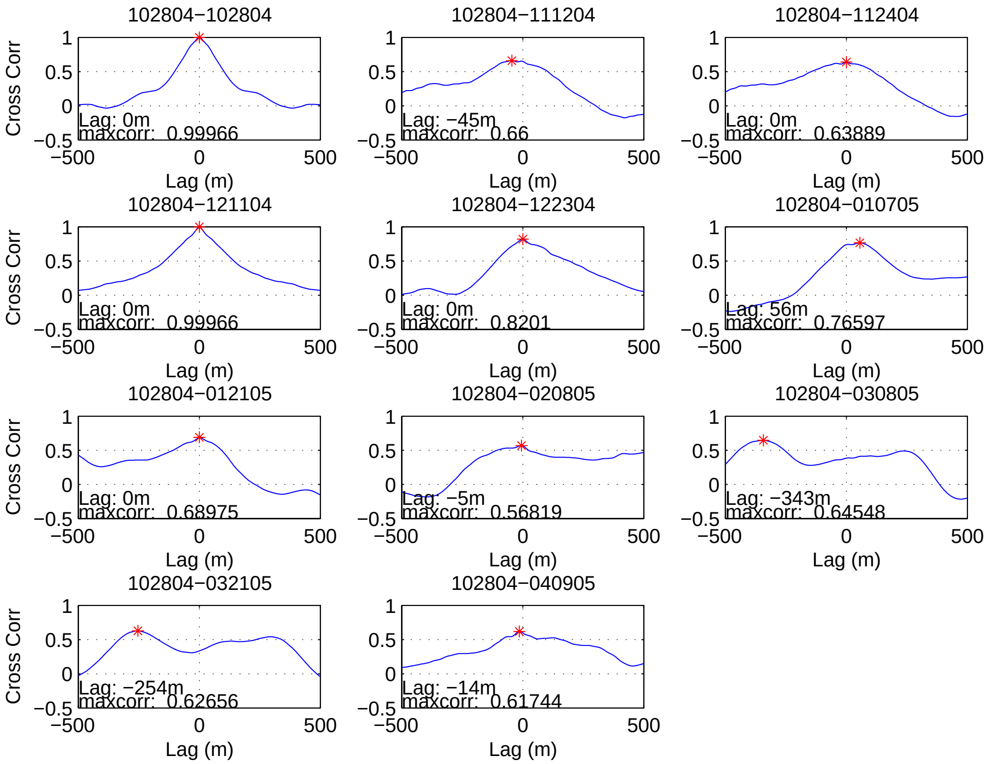

Figure 13. Normalized cross-correlations of +2m beach contour surveys for 16-18km distance south to north starting at Monterey Wharf #2 from 10/28/04-04/09/05. Cross-correlations sequence was restarted at the December 11, 2004 survey due to a large storm that affected the beach prior to the survey.

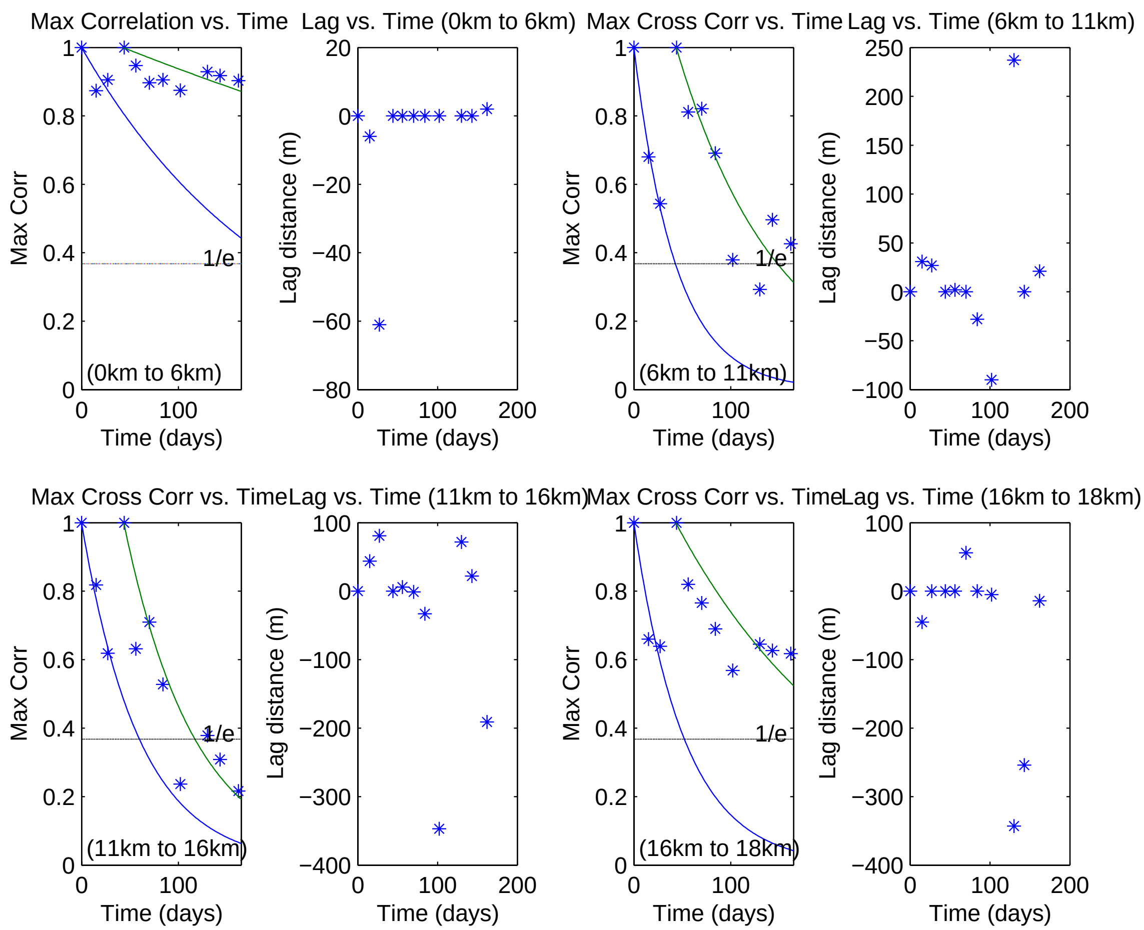

Figure 14. Maximum Cross-correlations and their corresponding lags plotted against time. Cross-correlations were restarted with the December 11, 2004 survey due to a high wave energy brought by a storm during the week prior to the survey that de-correlated the shoreline.

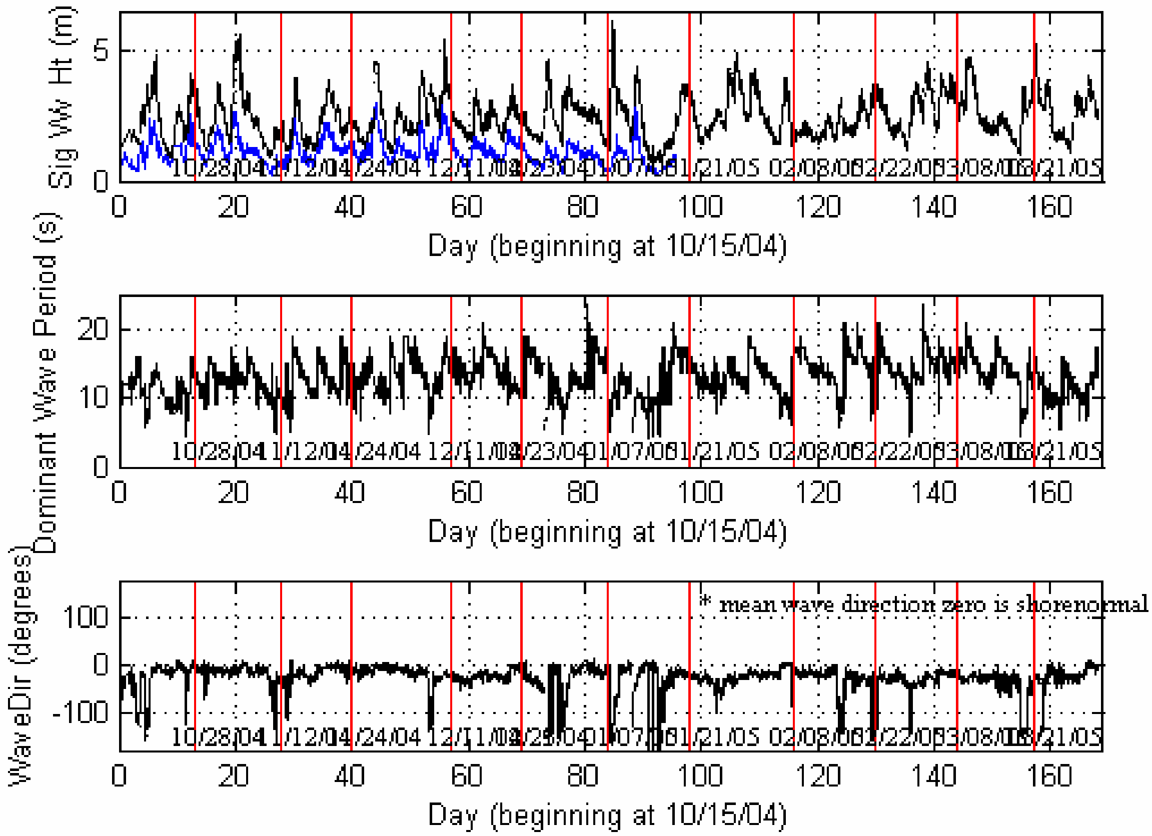

Figure 15. Offshore buoy wave heights, period, and mean direction overlaid with nearshore ADCP wave heights (blue).

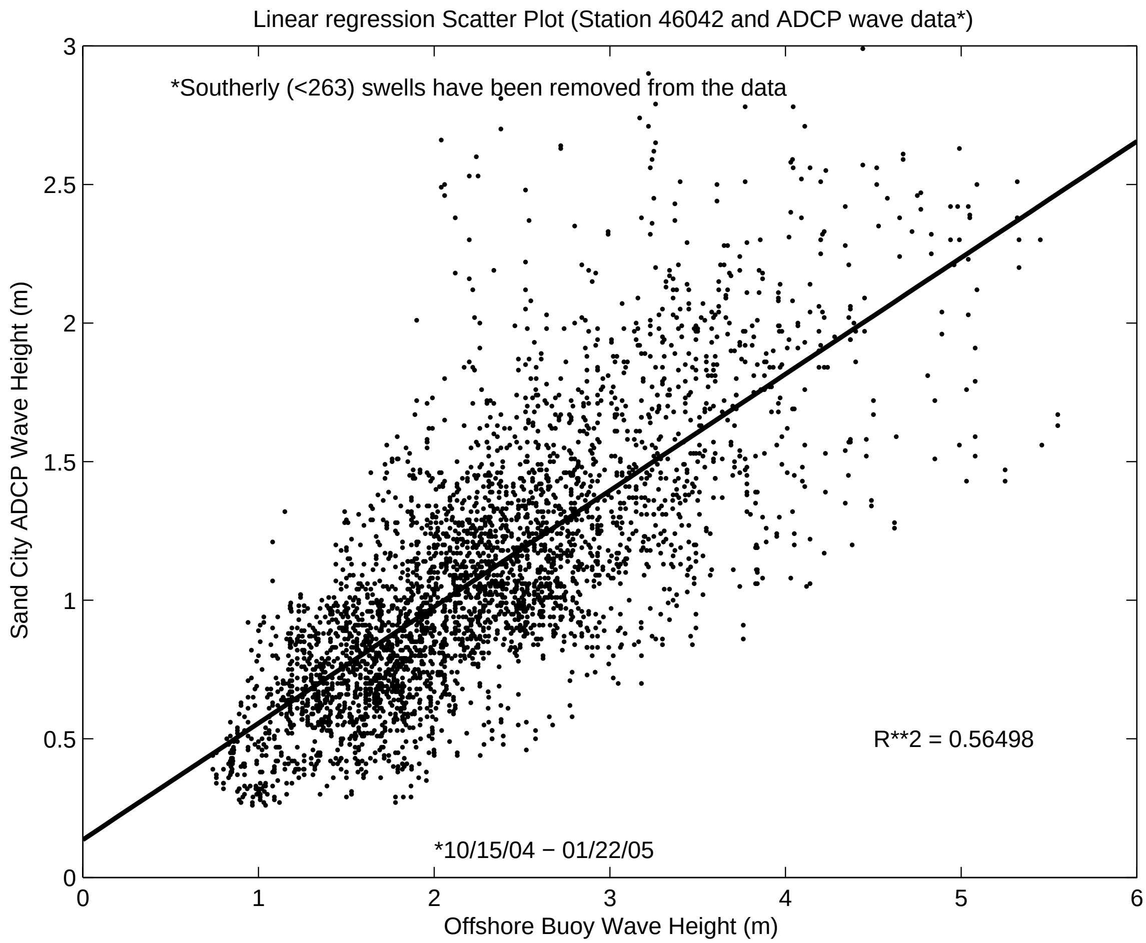

Figure 16. Linear regression scatter plot for the offshore buoy wave heights and the ADCP nearshore wave heights with southerly (>50º south of 313º) offshore swells removed. There is correlation of the offshore and nearshore wave data as it progresses into the Monterey Bay.

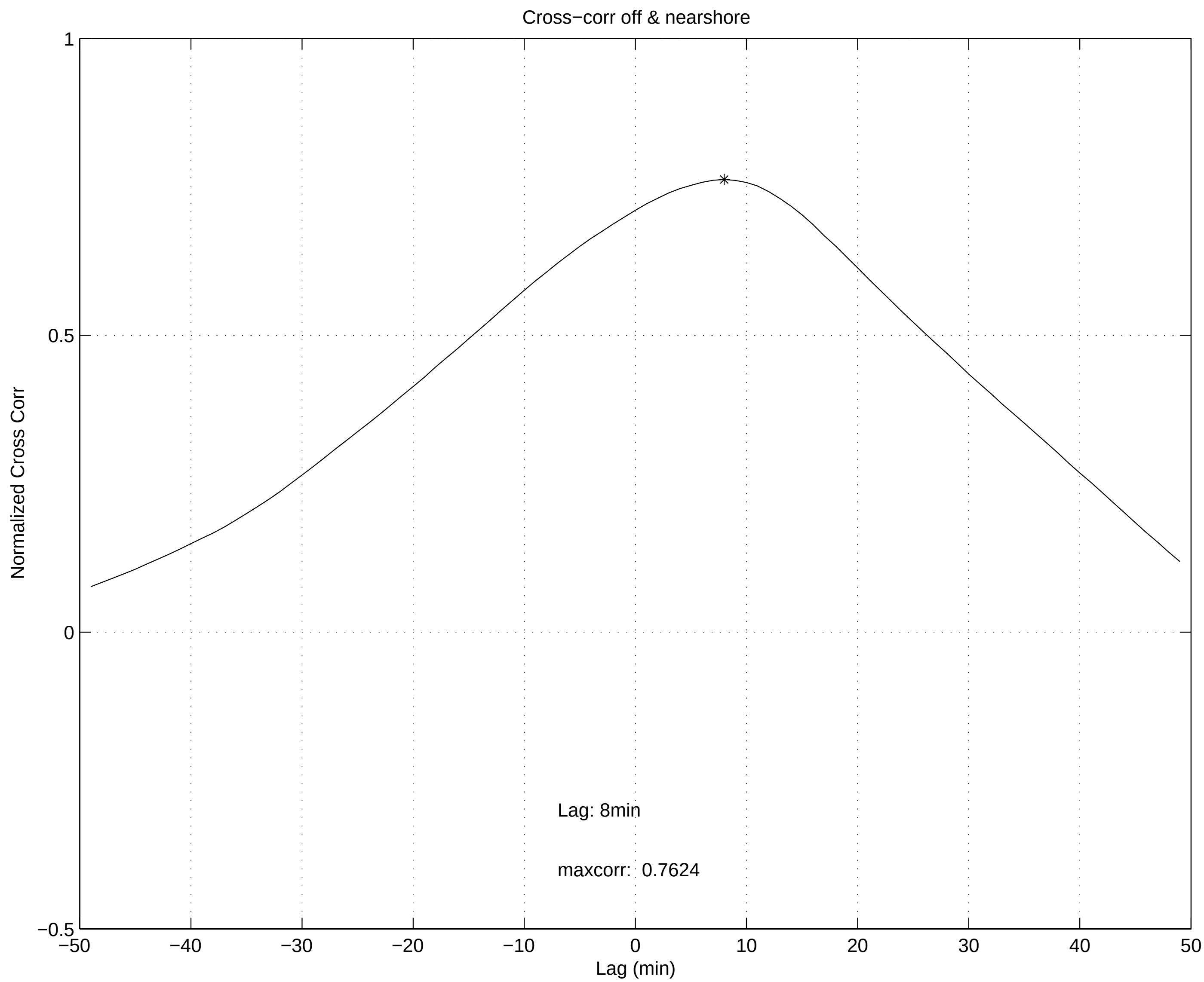

Figure 17. Cross-correlation of offshore wave buoy heights with ADCP wave heights. There is significant correlation between the two data sets with an eight minute temporal lag.

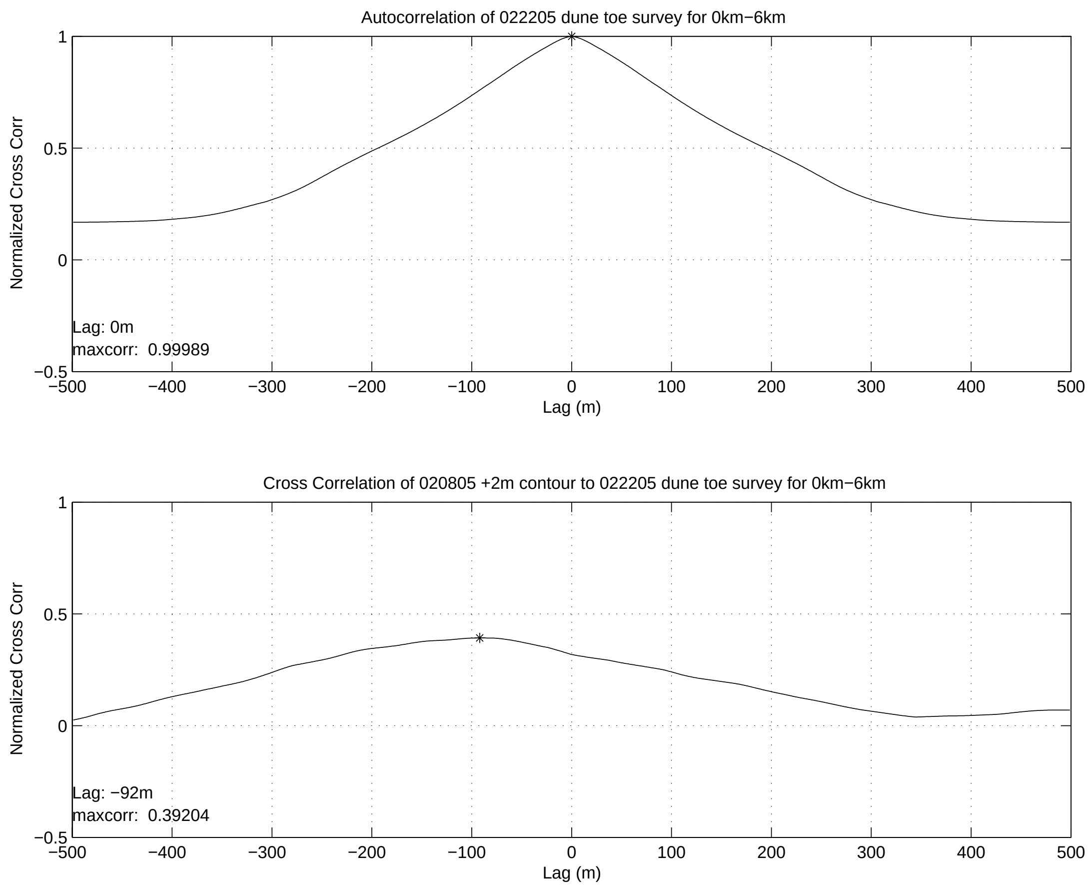

Figure 18. Dune toe cross-correlation with 02/08/05 +2m beach contour for 0-6km north of Monterey Wharf #2.

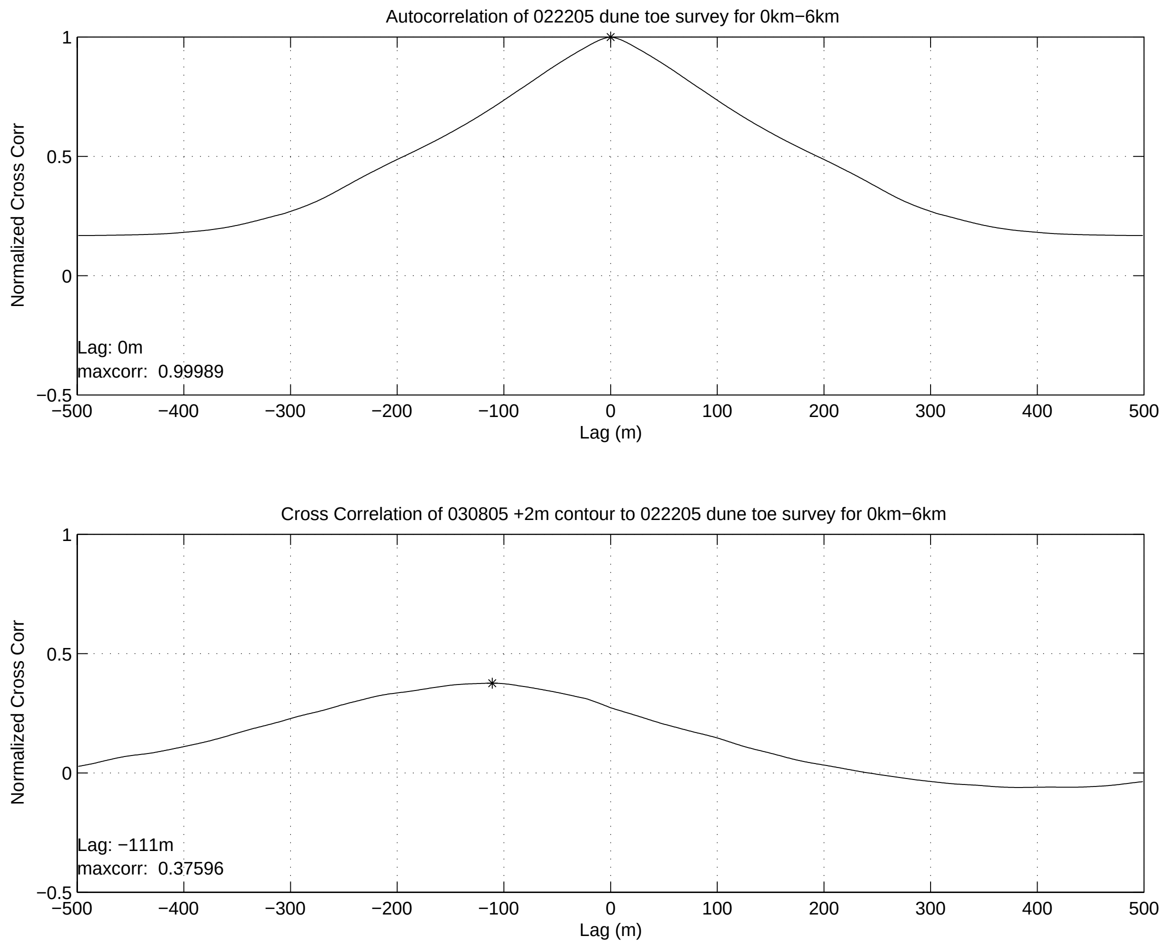

Figure 19. Dune toe cross-correlation with 03/08/05 +2m beach contour.

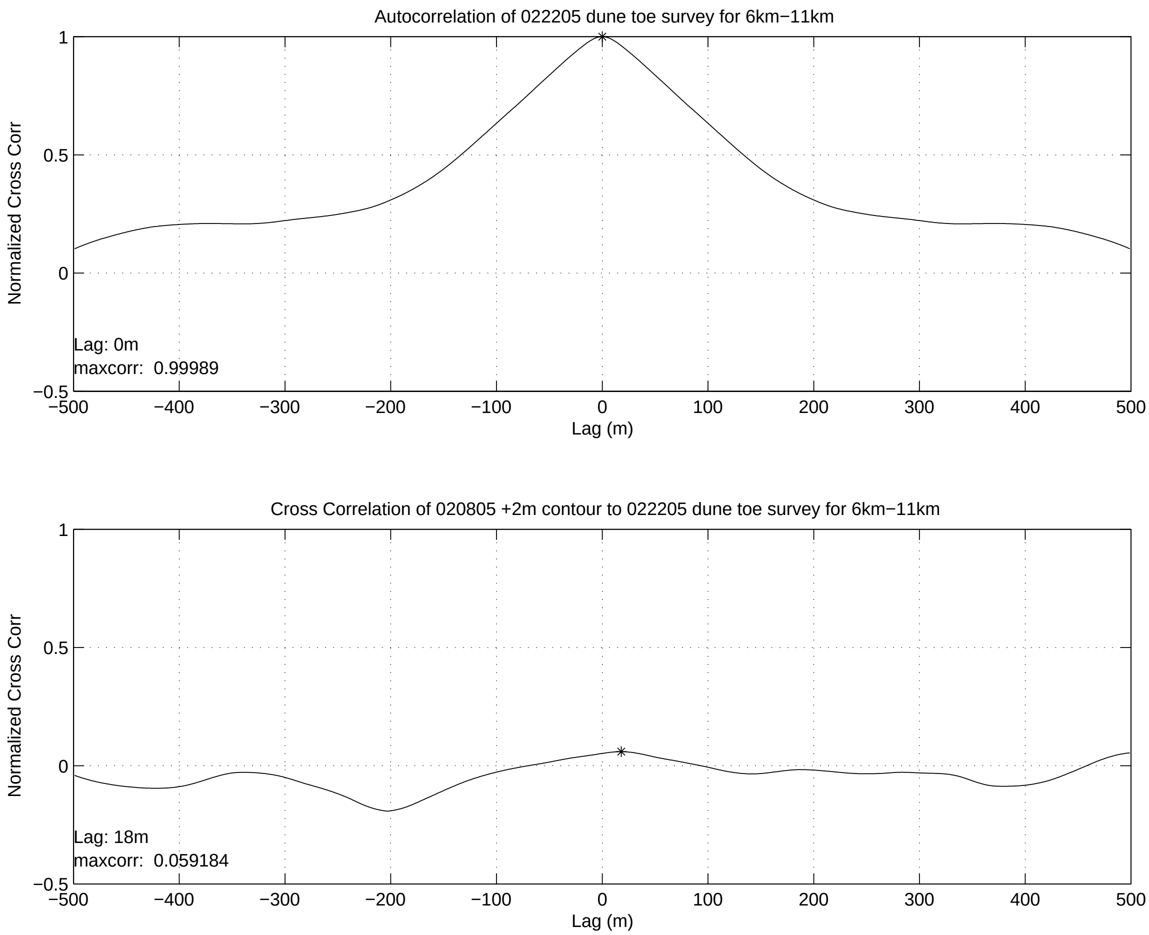

Figure 20. Dune toe cross-correlation with 02/08/05 +2m beach contour for 6-11km north of Monterey Wharf #2.

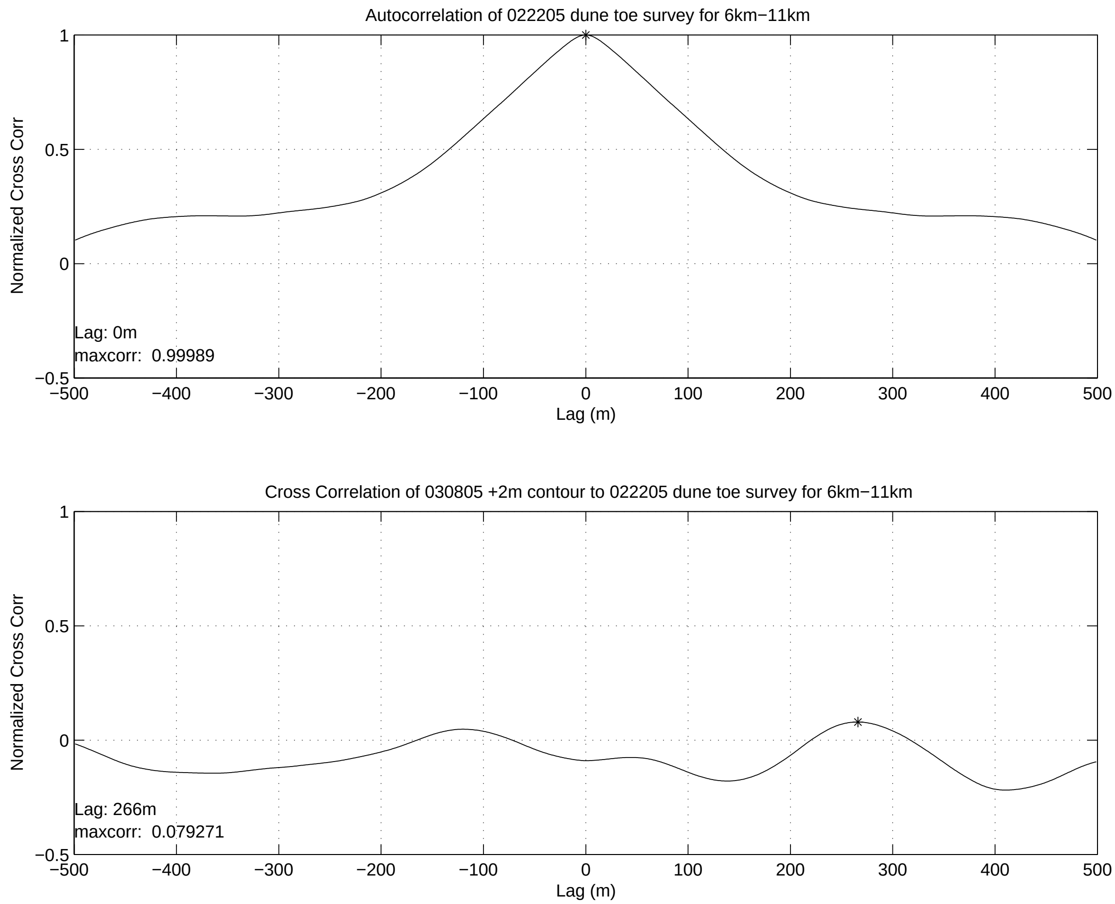

Figure 21. Dune toe cross-correlation with 03/08/05 +2m beach contour for 6-11km north of Monterey Wharf #2.

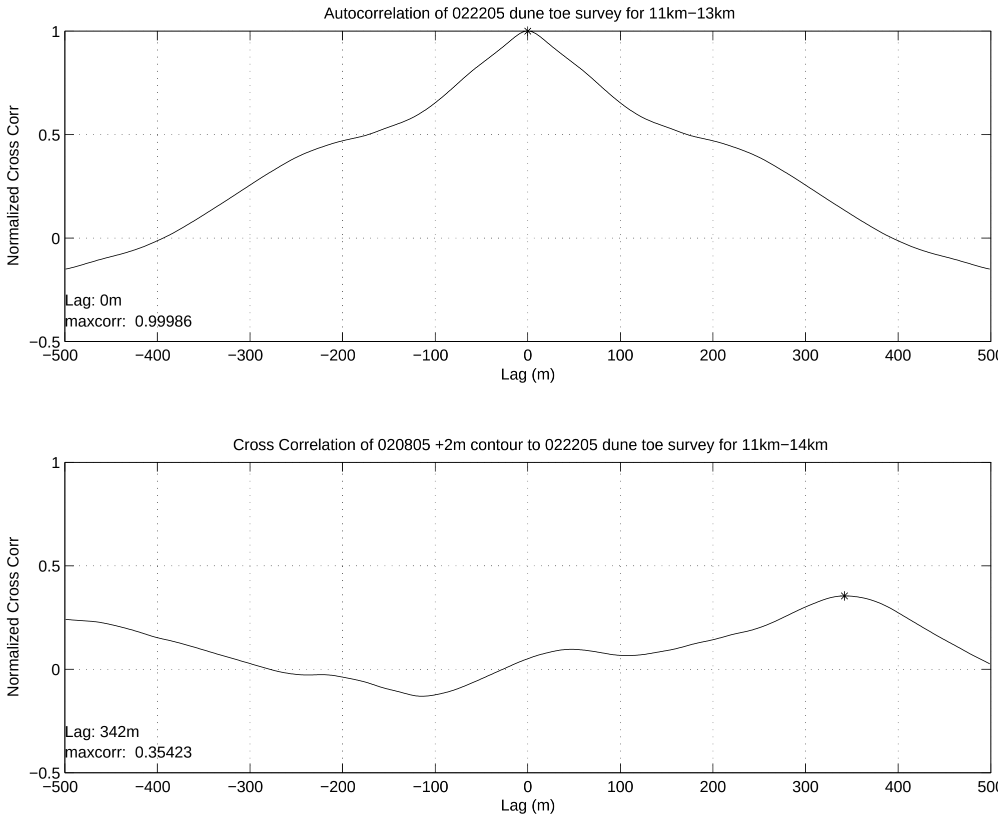

Figure 22. Dune toe cross-correlation with 02/08/05 +2m beach contour for 11-14km north of Monterey Wharf #2.

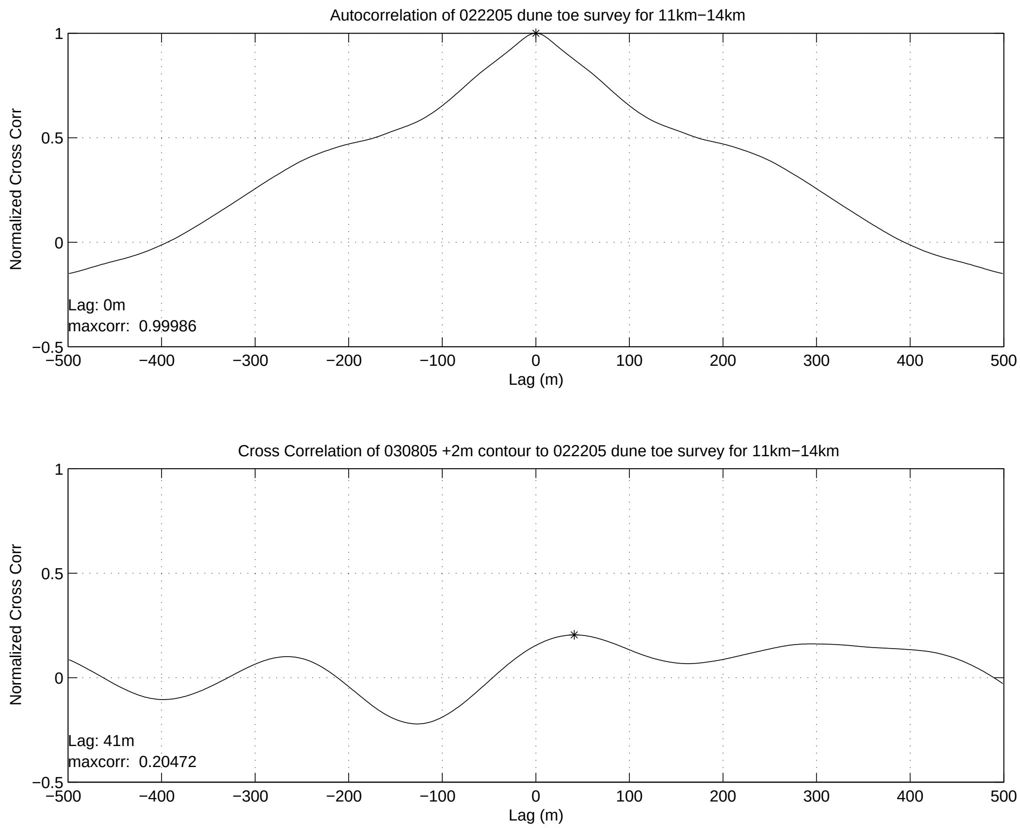

Figure 23. Dune toe cross-correlation with 03/08/05 +2m beach contour for 11-14km north of Monterey Wharf #2.

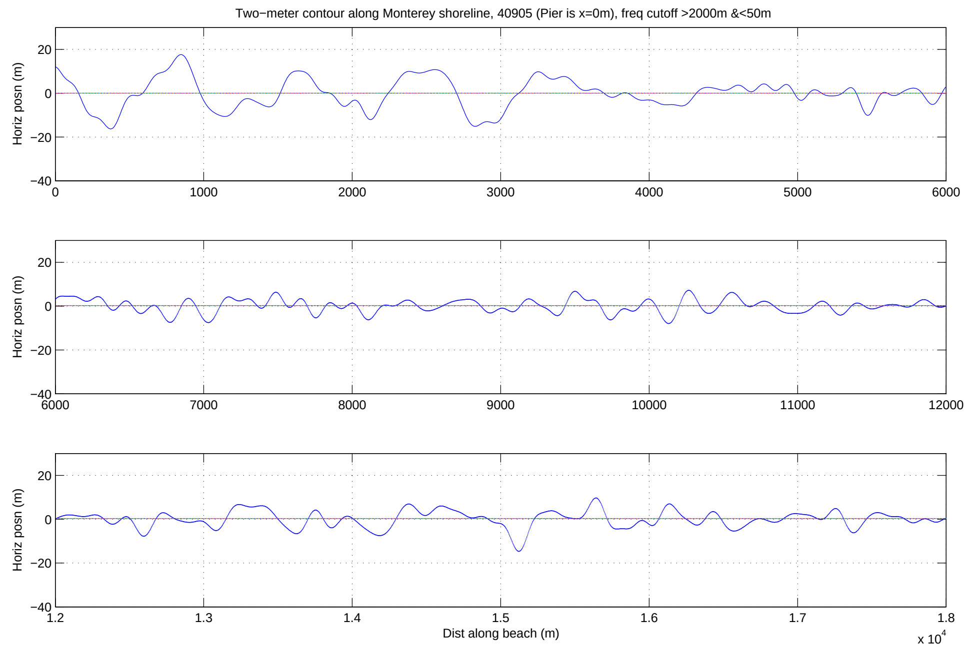

Figure 24. Adapted filter testing for cusps between 50-2000m for 04/09/05 survey.

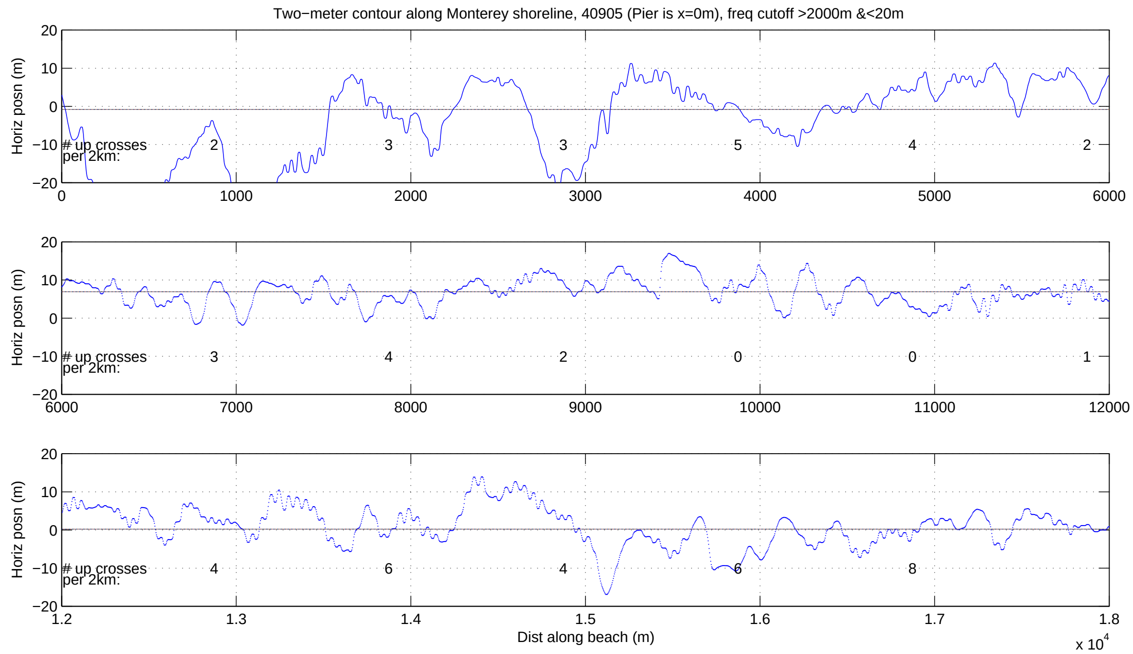

Figure 25. Adapted filter testing for cusps between 20-2000m for 04/09/05 survey.

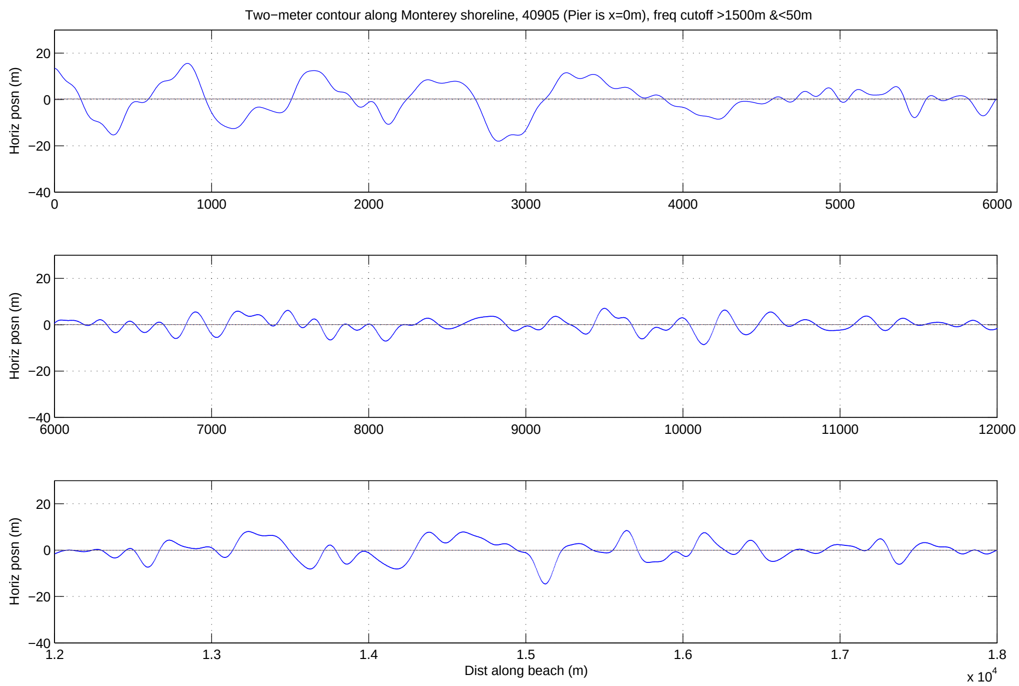

Figure 26. Adapted filter testing for cusps between 50-1500m for 04/09/05 survey.

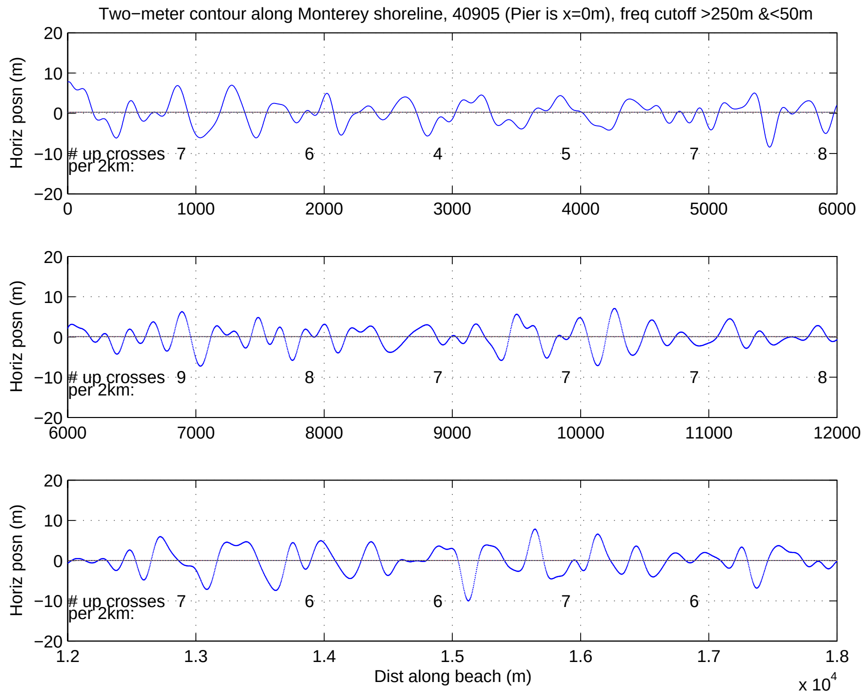

Figure 27. Adapted filter testing for cusps between 50-250m for 04/09/05 survey. This range of cusps filtered enough of the noise and larger embayment cusps features to get a reasonable count of the cusps.

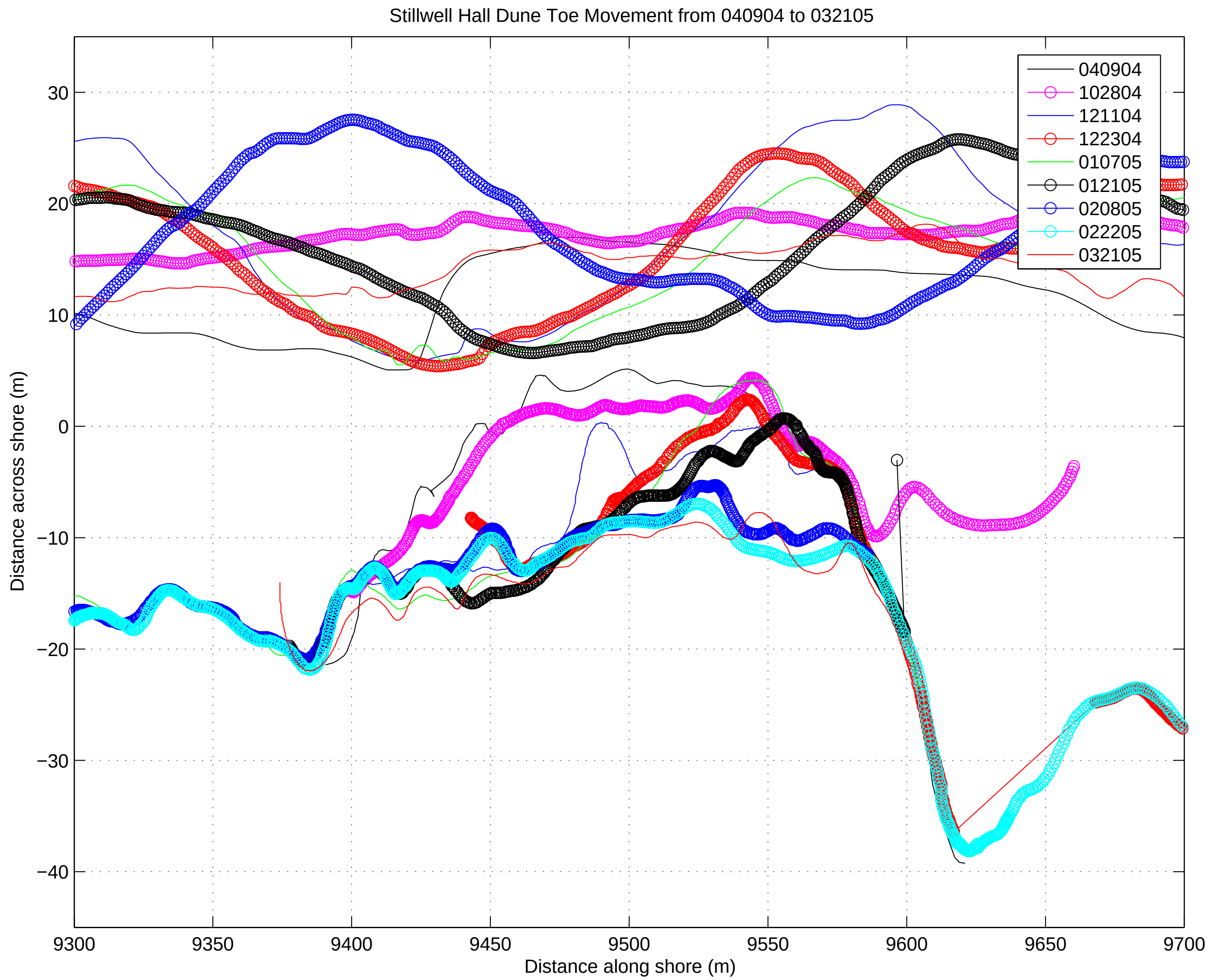

Figure 28. Overlay of all Stillwell hall surveys (bottom lines) and +2m beach contours (top lines). Positive y-axis is in the offshore direction and x-axis is increasing in the alongshore north direction showing progressive erosion associated with migration of cusp embayment.

Figure 29. Aerial photograph taken from 1000ft on February 5, 2005. The photo shows the rip channel extending seaward from the embayment cusp which is on the north end of the Stillwell Hall dune.

Stilwell Fort Ord Camera 1 snap: Fri Jan 07 1947GMT 2005

Figure 30. Photograph from Stillwell Hall camera site depicting rip channel (black arrow) extending from the embayment cusp on January 07, 2005.

Stilwell Fort Ord Camera 1 snap: Tue Feb 08 2053GMT 2005

Figure 31. Photograph from Stillwell Hall camera site depicting rip channel (black arrow) extending from the embayment cusp on February 08, 2005. The rip channel and embayment cusp has visually migrated north since January 7, 2005. There is noticeable erosion on the north side of Stillwell Hall dune (red arrow).

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B. TABLES

Number of cusps per 2km																	
	1km	2km	3km	4km	5km	6km	7km	8km	9km	10km	11km	12km	13km	14km	15km	16km	17km
200m	5	6	9	10	8	8	8	6	6	7	7	7	6	5	5	7	7
250m	7	6	4	5	7	8	9	8	7	7	7	8	7	6	6	7	6
300m	4	4	3	4	6	8	10	8	5	6	7	6	4	4	3	4	5
350m	3	2	3	5	5	7	10	7	5	6	7	8	7	5	4	6	7
400m	3	2	3	5	5	7	8	6	5	6	7	7	6	6	4	5	7
500m	2	2	3	3	6	8	8	7	5	6	8	7	5	4	2	5	8

Table 1. Trail and error process of varying low frequency cutoff from 200-500m in automatically counting cusps. The cusps were counted automatically by a zero up cross technique every 2000m, overlapping by 1000m. A length scale for the filter was chosen when as few cusps were missed by the automation process.

Number of Cusps per 2km and Average Cusp Length															
	28-Oct	12-Nov	24-Nov	11-Dec	23-Dec	7-Jan	21-Jan	8-Feb	8-Mar	21-Mar	9-Apr	Mean (m)	variance (m)	Standard deviation (m)	Coeff of Var (CV)
high lim	500	500	500	500	500	500	500	500	500	1000	250				
low lim	100	150	100	100	100	200	150	200	200	200	50				
1km	250	167	222	286	200	250	222	222	200	222	286	230	1310	36	0.16
2km	286	143	167	333	182	250	250	200	200	250	333	236	4082	64	0.27
3km	200	154	167	250	154	250	250	200	182	222	500	230	9379	97	0.42
4km	182	154	182	222	167	250	200	182	182	182	400	209	4684	68	0.33
5km	167	167	154	222	154	182	200	167	182	154	286	185	1567	40	0.21
6km	200	143	154	200	143	154	250	182	182	143	250	182	1603	40	0.22
7km	167	200	167	200	167	182	200	182	167	182	222	185	337	18	0.1
8km	154	182	182	200	182	222	182	200	182	200	250	194	635	25	0.13
9km	154	182	200	200	200	250	250	250	200	222	286	218	1440	38	0.17
10km	154	182	222	200	200	286	250	286	222	250	286	231	2021	45	0.19
11km	143	154	200	200	200	222	200	286	250	250	286	217	2232	47	0.22
12km	154	167	182	222	222	200	222	250	286	286	250	222	1949	44	0.2
13km	182	200	222	286	286	250	286	250	286	333	286	261	2003	45	0.17
14km	200	200	222	250	250	286	286	250	250	286	333	256	1620	40	0.16
15km	222	182	182	222	222	250	250	222	286	250	333	238	1906	44	0.18
16km	222	167	200	250	222	222	250	222	333	286	286	242	2127	46	0.19
17km	222	200	222	286	200	222	250	222	286	200	333	240	1908	44	0.18
Avg.	192	173	191	237	197	231	235	222	228	230	306	222	2400	46	0.2

Table 2. Number of cusps per 2000m and average cusp lengths for every 1000m. High and low limits for filtering were adapted for each individual survey. Also calculated is the average length of the cusps for every 1000 m and the variance and standard deviation.

Cross-Correlation of Dune Toe Survey with +2m Beach Contour Survey			
Survey Date	Distance	Max Corr	Lag
2/8/2005	0km-6km	0.39204	(-)92m
	6km-11km	0.059184	18m
	11km-14km	0.35423	342m
2/22/2005	0km-14km	0.99989	0m
3/8/2005	0km-6km	0.37596	(-)111m
	6km-11km	0.079271	266m
	11km-14km	0.20472	41m

Table 3. Autocorrelation of dune toe survey data (highlighted in grey) and cross-correlation with +2m beach contour survey data.

Embayment Cusp Migration Rates					
Survey Date	Cusp Migration Rate 0km-6km	Cusp Migration Rate 6km-11km	Cusp Migration Rate 11km-16km	Cusp Migration Rate 16km-18km	Tot Avg
10/28/2004	n/a	n/a	n/a	n/a	n/a
11/12/2004	0.4m/day	2.1m/day	2.9m/day	3m/day	2.1m/day
11/24/2004	4.6m/day	0.3m/day	2.5m/day	3m/day	2.36m/day
12/11/2004	n/a	n/a	n/a	n/a	n/a
12/23/2004	0m/day	0.2m/day	0.5m/day	0m/day	0.1m/day
1/7/2005	0m/day	0.1m/day	0.5m/day	3.7m/day	1.1m/day
1/21/2005	0m/day	0m/day	2.1m/day	3.7m/day	1.5m/day
2/8/2005	0m/day	1.9m/day	decorr	0.3m/day	0.7m/day
3/8/2005	0m/day	decorr	decorr	12.1m/day	6.1m/day
3/21/2005	0m/day	decorr	decorr	6.8m/day	3.4m/day
*3/21/2005	0.3m/day	1.7m/day	6.0m/day	7.2m/day	3.79m/day
4/9/2005	0.2m/day	decorr	decorr	12.6m/day	6.4m/day
Average	0.5m/day	0.9m/day	2.4m/day	5.2m/day	
* Migration rates measured from raw data.					

Table 4. Embayment cusp migration rates of all survey dates over four length scales and corresponding averages. Migration rates were obtained from lag distance divided by the time between surveys. *Migration rates were measured from the distances that cusps migrated between the two surveys (03/08/05-03/21/05).

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